

A Thesis Submitted for the Degree of PhD at the University of Warwick

Permanent WRAP URL:

<http://wrap.warwick.ac.uk/111384/>

Copyright and reuse:

This thesis is made available online and is protected by original copyright.

Please scroll down to view the document itself.

Please refer to the repository record for this item for information to help you to cite it.

Our policy information is available from the repository home page.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

**THE EPIDEMIOLOGY OF FEMOROACETABULAR
IMPINGEMENT SYNDROME**

**EDWARD J DICKENSON
MBChB, MRCS**

**DOCTOR OF PHILOSOPHY IN THE HEALTH SCIENCES
WARWICK MEDICAL SCHOOL, UNIVERSITY OF
WARWICK**

JULY 2018

List of Tables	5
List of Figures	7
Acknowledgements	11
Declarations	12
Publications.....	12
Abstract	14
Abbreviations	15
Research Training.....	16
Courses Attended	16
Conferences Attended.....	16
1 Introduction	17
1.1 Background	17
1.2 Hip Anatomy and Function	18
1.3 Hip Pathology.....	26
1.4 Thesis Aims and Objective	35
2 What is the prevalence of cam and pincer hip morphology; a systematic review.....	37
2.1 Introduction	38
2.2 Objectives.....	39
2.3 Methods.....	39
2.4 Results.....	43
2.5 Discussion	63
2.6 Reflections	67
3 FAI Consensus Meeting.....	71
3.1 Introduction	72
3.2 Objectives.....	73
3.3 Methods.....	74
3.4 Results	78
3.5 Discussion	85
3.6 Conclusion.....	88
3.7 Reflections	88
4 Developing criteria to define cam and pincer morphology	93
4.1 Introduction	94

4.2	Cam Morphology.....	95
4.3	Pincer Morphology	112
4.4	Discussion	132
4.5	Conclusion.....	143
4.6	Reflections	143
5	Prevalence of Cam Morphology in the General Population.....	148
5.1	Introduction	149
5.2	Objectives.....	149
5.3	Methods.....	149
5.4	Results	154
5.5	Discussion	159
5.6	Conclusion.....	163
5.7	Reflections	163
6	Prevalence of Cam Morphology in Elite Golfers	166
6.1	Introduction	168
6.2	Objectives.....	169
6.3	Methods.....	169
6.4	Results	173
6.5	Discussion	180
6.6	Conclusion.....	186
6.7	Reflections	186
7	Does cam and pincer morphology, or FAI syndrome cause hip osteoarthritis; a systematic review?	190
7.1	Introduction	190
7.2	Objectives.....	193
7.3	Methods.....	193
7.4	Results	194
7.5	Discussion	214
7.6	Conclusion.....	223
7.7	Reflections	223
8	Is it feasible to undertake an efficacy trial of arthroscopic FAI surgery using cartilage mapping as a proxy outcome?	226
8.1	Introduction	227
8.2	Objectives.....	232
8.3	Methods.....	232

8.4	Results.....	241
8.5	Discussion	249
8.6	Conclusion.....	259
8.7	Reflections	259
9	Discussion and Conclusions.....	263
9.1	Review of thesis objectives.....	263
9.2	Summary of new findings.....	263
9.3	New findings in the context of our present understanding and on-going research.....	265
9.4	Future Research.....	268
10	References.....	272
11	Appendix.....	294
11.1	Chapter 1; additional material.....	294
11.2	Chapter 4; additional material.....	309
11.3	Chapter 6 additional material.....	377

List of Tables

TABLE 1 RISK FACTORS FOR HIP OA ³⁷	28
TABLE 2 MEDLINE SEARCH STRATEGY	41
TABLE 3 MEASURES OF CAM MORPHOLOGY	47
TABLE 4 MEASURES OF Pincer MORPHOLOGY	47
TABLE 5: INCLUDED STUDIES RISK OF BIAS.....	48
TABLE 6 DESCRIPTION AND DEMOGRAPHICS OF INCLUDED STUDIES	52
TABLE 7 PANEL MEMBERS.....	76
TABLE 8 MANUSCRIPTS CIRCULATED TO PANEL MEMBERS IN ADVANCE OF THE MEETING.....	77
TABLE 9 PROPOSED ANSWERS FOR EACH TOPIC	78
TABLE 10 AGREEMENT ON TERMINOLOGY RELATING TO FEMOROACETABULAR IMPINGEMENT. 80	
TABLE 11 SAMPLE SIZE CALCULATION FOR DETERMINING THE CONFIDENCE INTERVAL WIDTH OF A ROC GIVEN AN ANTICIPATED FALSE POSITIVE AND TRUE POSITIVE RATE FOR A CASE TO CONTROL RATIO OF 1:2. TABLE ADAPTED FROM MACHIN 2011 ¹⁹⁵	99
TABLE 12 DEMOGRAPHICS OF CASES	100
TABLE 13 MEAN ALPHA ANGLE AROUND THE FEMORAL NECK FOR CASES AND CONTROLS	102
TABLE 14 SUMMARY OF ROC AREA UNDER CURVE.....	107
TABLE 15 CONTINGENCY TABLES FOR DETERMINING THE PRESENCE OF CAM MORPHOLOGY USING THE MEAN OF A ANGLES BETWEEN 12-3 O’CLOCK GREATER THAN 52°	111
TABLE 16 DEMOGRAPHICS OF CASES WITH MIXED AND Pincer TYPE FAI SYNDROME	121
TABLE 17 MEAN SEAS AROUND THE ACETABULAR AXIS FOR CASES AND CONTROLS	123
TABLE 18 MEAN CEA, ACETABULAR ANTEVERSION AND ACETABULAR DEPTH FOR CASES AND CONTROLS.....	130
TABLE 19 AUC FOR MEASURES OF Pincer MORPHOLOGY.....	130
TABLE 20 CONTINGENCY TABLES FOR DETERMINING THE PRESENCE OF Pincer MORPHOLOGY USING A SEA AT 2 O’CLOCK GREATER THAN 80.5°	132
TABLE 21 RANGE OF SAMPLE SIZES FOR GIVEN PREVALENCE ESTIMATE AND CONFIDENCE INTERVAL WIDTH.....	154
TABLE 22 ETHNICITY OF INCLUDED SUBJECTS	155
TABLE 23 ENGLISH INDEX OF MULTIPLE DEPRIVATION 2015.....	155
TABLE 24 RURAL URBAN CLASSIFICATION	156
TABLE 25 PREVALENCE OF CAM MORPHOLOGY.....	158
TABLE 26 PREVALENCE OF Pincer MORPHOLOGY IN HIPS AND PARTICIPANTS	159
TABLE 28 PHYSICAL EXAMINATION FINDINGS.....	175
TABLE 29 PROXIMAL FEMORAL MORPHOLOGY	178
TABLE 30 ACETABULAR MORPHOLOGY ASSESSED BY SUBTENDED EDGE ANGLES	178
TABLE 31 MULTIPLE LINEAR REGRESSION MODEL OF IHOT12 SCORES.....	179
TABLE 32 RISK OF BIAS ASSESSMENT FOR INCLUDED STUDIES	203
TABLE 33 DESCRIPTION OF INCLUDED STUDIES AND ASSESSMENT OF ASSOCIATION WITH HIP OA	205

TABLE 34 CATEGORIES OF BRADFORD HILL CRITERIA WHERE EVIDENCE IS SUFFICIENT TO DEMONSTRATE CAUSALITY	219
TABLE 35 RECRUITMENT SUCCESS IN UK FASHION AND MRI FOLLOW UP	242
TABLE 36 BASELINE DEMOGRAPHICS.....	243
TABLE 37 TIME BETWEEN BASELINE MRI, RANDOMISATION, TREATMENT AND FOLLOW UP MRI	244
TABLE 38 OUTCOME OF SURGICAL REVIEW PANEL.....	245
TABLE 39 FOLLOW UP MRI T2* MEASUREMENTS.....	248
TABLE 40 CHANGES IN HOAMS AND CARTILAGE THICKNESS BETWEEN SURGERY AND PHT	248
TABLE 41 COMPARISON OF DIFFERENT T2* SCANNING PROTOCOLS.....	253
TABLE 42 SUB GROUP ANALYSIS OF T2* VALUES.....	254
TABLE 43 FUTURE RESEARCH QUESTIONS AND THEIR RANK BY THE PANEL OF THE “2016 WARWICK AGREEMENT”	269
TABLE 44 RESULTS OF CRICKETS QUESTIONNAIRE, PHYSICAL AND MRI EXAMINATION.....	379

List of Figures

FIGURE 1 ACETABULAR RIM DEMONSTRATING UNDULATING PROFILE. A ISCHIAL EMINENCE B ILLIOISCHIAL TROUGH C ILIAC EMINENCE D ILIOPUBIC TROUGH E PUBIC EMINENCE IMAN INFERIOR MARGIN OF ACETABULAR NOTCH. SOURCE VANDENDUSSCH ET AL ¹⁵	20
FIGURE 2 POSITION OF THE ACETABULUM WITHIN THE PELVIS, DETERMINED FROM THE ASIS. THE CX:DX IN MALES IS 10% AND 8% IN FEMALES. THE CY:DY IS 36% IN AMELS AND 32% IN FEMALES AND THE CZ:DZ IS 39% IN MALES AND 36% IN FEMALES. SOURCE DANDACHLI ET AL ¹⁸	21
FIGURE 3 DIAGRAM OF THE LATERAL VIEW OF THE PELVIS SHOWING THE PELVIC INCIDENCE, SACRAL SLOPE AND PELVIC TILT. SOURCE LEGAYE ET AL ²¹	22
FIGURE 4 CROSS SECTIONAL DIAGRAM OF HYALINE CARTILAGE. SOURCE STEWARD 2011 ²⁶ (A) CHONDROCYTE AND (B) COLLAGEN FIBRE ORGANISATION IN ARTICULAR CARTILAGE STZ: SUPERFICIAL TRANSITIONAL ZONE	24
FIGURE 5 PATHOGENESIS OF OSTEOARTHRITIS ADAPTED FROM DIEPPE. THE CLASSIFICATION AND DIAGNOSIS OF OSTEOARTHRITIS 1995 ⁴⁴	28
FIGURE 6 NORMAL CONFIGURATION OF HIP WITH SUFFICIENT JOINT CLEARANCE TO ALLOW UNRESTRICTED RANGE OF MOTION (TOP). IN PINCER IMPINGEMENT ACETABULAR OVER COVERAGE LEADS TO EARLY CONTACT BETWEEN THE FEMORAL HEAD NECK JUNCTION AND ACETABULAR RIM (MIDDLE). IN CAM IMPINGEMENT THE ASPHERICAL ASPECT OF FEMORAL HEAD NECK JUNCTION INTRUDES INTO THE ACETABULUM DURING MOTION; TYPICALLY FLEXION AND INTERNAL ROTATION (BOTTOM). SOURCE TANNAST ET AL 2007. ⁴⁵	29
FIGURE 7 DIAGRAMMATIC REPRESENTATION OF HOW TO MEASURE AN ALPHA ANGLE. SOURCE NOTZLI ET AL 2002 ⁶²	32
FIGURE 8 PRISMA FLOW DIAGRAM OF SEARCH RESULT	43
FIGURE 9 CONSENSUS MEETING FLOW DIAGRAM	75
FIGURE 10 SELECTION OF CAM CASES TO BE ANALYSED.....	100
FIGURE 11 HISTOGRAMS OF ALPHA ANGLES MEASURED AT 12, 1, 2 AND 3 O'CLOCK AND THE MEAN OF ALPHA ANGLES MEASURED BETWEEN 12 AND 3 O'CLOCK, FOR CASES AND CONTROLS.....	103
FIGURE 12 RADAR PLOTS OF ALL CAM MORPHOLOGY CASE AND CONTROL HIPS SHOWING ALPHA ANGLES MEASURED AROUND THE FEMORAL HEAD NECK JUNCTION	105
FIGURE 13 RADAR PLOT OF ALPHA ANGLES AROUND THE FEMORAL HEAD NECK JUNCTION, SHOWING MEAN VALUES FOR CASES AND CONTROLS	106
FIGURE 14 ROC CURVES FOR THE A ANGLES MEASURED AT DIFFERENT POSITIONS ON FEMORAL HEAD NECK JUNCTION IN CAM TYPE FAI SYNDROME	107
FIGURE 15 ROC CURVES FOR THE MEAN OF A ANGLES MEASURED BETWEEN 12-3 O'CLOCK- THE MEASURE WITH THE GREATEST AUC.	108
FIGURE 16 ROC CURVES FOR THE A ANGLES MEASURED AT 12 O'CLOCK	108
FIGURE 17 ROC CURVES FOR THE A ANGLES MEASURED AT 1 O'CLOCK.....	109
FIGURE 18 ROC CURVES FOR THE A ANGLES MEASURED AT 2 O'CLOCK.....	109

FIGURE 19 ROC CURVES FOR THE A ANGLES MEASURED AT 3 O'CLOCK.....	110
FIGURE 20 ROC CURVES FOR THE A ANGLES MEASURED AT 4 O'CLOCK.....	110
FIGURE 21 ROC CURVES FOR THE A ANGLES MEASURED AT 7 O'CLOCK.....	111
FIGURE 22 ANTERIOR PELVIC PLANE.....	114
FIGURE 23 DIRECT LATERAL VIEW OF PELVIS. THE BLUE POINTS REPRESENT THE ASIS AND PUBIC TUBERCLE, DEFINING THE ANTERIOR PELVIC PLANE. THE LINE REPRESENT THE ACETABULAR AXIS.....	114
FIGURE 24 CT MULTI-PLANAR RECONSTRUCTION ORIENTATED TO ANTERIOR PELVIC PLANE ...	115
FIGURE 25 CT IN ANTERIOR PELVIC PLANE CENTRED ON MIDDLE OF FEMORAL HEAD, AND THEN ROTATED AROUND THE CORONAL AXIS 45° (SEE RIGHT HAND IMAGE).....	116
FIGURE 26 FOLLOWING 45° ABDUCTION IN CORONAL PLANE (RIGHT HAND IMAGE), THE 15° ANTEVERSION HAS BEEN MEASURED (BOTTOM LEFT IMAGE) AND APPLIED TO CREATE THE ACETABULAR AXIS.....	116
FIGURE 27 SEA ARE MEASURED BETWEEN THE ACETABULAR AXIS (LINE 1), THE CENTRE OF THE FEMORAL HEAD AND THE RIM OF THE ACETABULUM (LINE 2). THIS POSITION CORRESPONDS TO 3 O'CLOCK. THE SEA IS 68 DEGREES.....	117
FIGURE 28 ONCE THE SEA HAVE BEEN MEASURED AT ALL AVAILABLE POSITIONS; RIGHT HAND IMAGE 12 O'CLOCK SUPERIORLY AND 6 O'CLOCK INFERIORLY, BOTTOM LEFT 3 O'CLOCK AT TOP AND 9 O'CLOCK AT BOTTOM, THE IMAGE PLANE IS ROTATED 30° ON THE SAGITTAL OBLIQUE (TOP LEFT) IN ORDER TO MEASURE THE REMAINING POSITIONS AROUND ACETABULAR AXIS. ROTATING 30° CLOCKWISE FOR A LEFT HIP (ANTI CLOCKWISE FOR RIGHT HIP) ON THE SAGITTAL OBLIQUE WILL THEN SHOW THE 11 O'CLOCK POSITION ON THE ACETABULAR RIM AT THE TOP OF THE RIGHT HAND IMAGE AND THE 2 O'CLOCK POSITION ON THE ACETABULAR RIM AT THE TOP OF THE BOTTOM LEFT IMAGE.....	117
FIGURE 29 FOLLOWING 30° CLOCKWISE ROTATION AROUND ACETABULAR AXIS SEAS ARE MEASURED AT 11 AND 5 O'CLOCK (RIGHT HAND IMAGE) AND 8 AND 2 O'CLOCK (BOTTOM RIGHT). TO COMPLETE THE 12 MEASUREMENTS A FURTHER 30° CLOCKWISE ROTATION AROUND ACETABULAR AXIS (TOP LEFT) IS REQUIRED.....	118
FIGURE 30 VIEW OF THE ACETABULUM ALONG THE ACETABULAR AXIS (RED DOT). THE BLUE DOTS REPRESENT THE ASIS AND PUBIC TUBERLE. THE 3, 12 AND 9 O'CLOCK POSITIONS ARE IDENTIFIED.....	118
FIGURE 31 FLOW DIAGRAM FOR SELECTION OF CASES AND CONTROLS TO ASSESS PINCER MORPHOLOGY.....	121
FIGURE 32 HISTOGRAMS OF SEA MEASURED AROUND THE ACETABULAR AXIS, FOR CASES AND CONTROLS.....	124
FIGURE 33 RADAR PLOTS OF ALL PINCER MORPHOLOGY CASE AND CONTROL HIPS SHOWING SEA MEASURED AROUND THE ACETABULAR AXIS. CASES THAT WERE DEFINED AND PINCER AND MIXED TYPE FAI SYNDROME ARE DISPLAYED SEPARATELY.....	128
FIGURE 34 RADAR PLOT OF MEAN SEA FOR CASES AND CONTROLS MEASURED AROUND THE ACETABULAR AXIS.....	129
FIGURE 35 ROC CURVE FOR ASSESSMENT OF PINCER MORPHOLOGY USING SEA AT 2 O'CLOCK...	131

FIGURE 36 FLOW DIAGRAM	154
FIGURE 37 THE POPULATION DISTRIBUTION OF THE MEAN OF ALPHA ANGLES MEASURED BETWEEN 12 AND 3 O’CLOCK.....	157
FIGURE 38 THE POPULATION DISTRIBUTION OF THE SEA MEASURED AT 2 O’CLOCK	158
FIGURE 39 PARTICIPANTS ASSESSED	173
FIGURE 40 THE POPULATION DISTRIBUTION FOR MEAN ALPHA ANGLES MEASURED BETWEEN 12 AND 3 O’CLOCK FOR LEAD AND TRAIL HIPS.....	176
FIGURE 41 THE DISTRIBUTION OF SEAS MEASURED AT 2 O’CLOCK FOR LEAD AND TRAIL HIPS...	177
FIGURE 42 THE DISTRIBUTION OF ANTE-TORSION FOR LEAD AND TRAIL HIPS.....	177
FIGURE 43 PRISMA FLOW DIAGRAM	195
FIGURE 44 POSSIBLE ASSOCIATIONS BETWEEN GENERAL POPULATION, SUBJECTS WITH CAM AND Pincer Morphology, FAI Syndrome and OA.	221
FIGURE 45 PLOT OF TRANSVERSE RELAXATION AGAINST TIME. T2* DECAY IS MEASURED ON GRADEINT ECHO SEQUENCE. T2 DECAY IS DETERMINED ON SPIN ECHO SEQUENCES. SOURCE CHAVHAN ET AL 2009. ³⁰⁵	231
FIGURE 46 CONSORT DIAGRAM	242
FIGURE 47 TIME BETWEEN BASELINE MRI AND RANDOMISATION	244
FIGURE 48 TIME BETWEEN RANDOMISATION AND TREATMENT.....	244
FIGURE 49 T2* MAP GENERATED IN FUNCTOOL. IN THIS ILLUSTRATION THE T2* VALUES FOR EACH VOXEL ARE REPRESENTED BY DIFFERENT COLOURS; SEE KEY ON LEFT SIDE OF IMAGE. THE DARK RED COLOUR REPRESENTS A T2* VALUE OF 30MS AND THE DARK BLUE REPRESENT A T2* VALUE OF 0MS.	246
FIGURE 50 REGIONS OF INTEREST DRAWN USING T1 FAT SATURATED SPGR 3D SAGITTAL SLICE IN LINE WITH MID POINT OF FEMORAL HEAD. THE 90° ANGLE IS IN LINE WITH THE TRANSVERSE ACETABULAR LIGAMENT. ROIS WERE LABELED CLOCKWISE; ROI 1 IN THE ANTERIOR MOST ASPECT TO ROI 8 IN THE MOST POSTERIOR ASPECT.	246
FIGURE 51 T2* MAP GENERATED IN FUNCTOOL. IN THIS ILLUSTRATION THE T2* VALUES FOR EACH VOXEL ARE REPRESENTED BY DIFFERENT COLOURS; SEE KEY ON LEFT SIDE OF IMAGE (DIFFERENT KEY TO FIGURE 37). THE DARK RED COLOUR REPRESENTS A T2* VALUE OF 64MS AND THE DARK BLUE REPRESENT A T2* VALUE OF 0MS. NOTE POOR MAP FIT AT JUNCTION BETWEEN ACETABULAR SUBCHONDRAL BONE AND ARTICULAR CARTILAGE WHERE THE VOXEL T2* VALUE IS OUTSIDE THE SCALE AND THEREFORE DISPLAYED IN BLACK.....	247
FIGURE 52 PLOT OF TRANSVERSE RELAXATION SIGNAL (Y AXIS) AGAINST TES (X AXIS) FOR A SINGLE ROI. THE GREEN LINE DISPLAYS THE RAW SINGLE. THE RED LINE DISPLAYS THE EXPONENTIAL DECAY CURVE FITTED BY FUNCTOOL. THIS GRAPH DISPLAYS A WELL FITTING SIGNAL DECAY CURVE.....	247
FIGURE 53 PLOT OF TRANSVERSE RELAXATION SIGNAL (Y AXIS) AGAINST TES (X AXIS) FOR A SINGLE ROI. THE GREEN LINE DISPLAYS THE RAW SINGLE. THE RED LINE DISPLAYS THE EXPONENTIAL DECAY CURVE FITTED BY FUNCTOOL. THIS GRAPH DISPLAYS A POORLY	

FITTING SIGNAL DECAY CURVE; THIS IS LIKELY TO HAVE PROVIDED THE IMPOSSIBLE VALUES FOR T2*	248
FIGURE 54 RELATIONSHIP BETWEEN CAM AND PINCER MORPHOLOGY, FAI SYNDROME AND HIP OA.....	266
FIGURE 55 DIAGRAMMATIC REPRESENTATION OF HOW TO MEASURE AN ALPHA ANGLE (SOURCE NOTZLI ET AL 2002 ⁶²).....	295
FIGURE 56 DIAGRAMMATIC REPRESENTATION OF TRIANGULAR INDEX (SOURCE: GOSVIG ET AL 2007 ⁶³).....	296
FIGURE 57 CROSS TABLE LATERAL XRAY OF RIGHT HIP DEMONSTRATING HOW HEAD NECK OFFSET IS DETERMINED (SOURCE PEELLE 2005 ³⁴¹)	297
FIGURE 58 “PISTOL GRIP” DEFORMITY (SOURCE STULBERG ET AL 1975 ⁴⁹).....	298
FIGURE 59 DIAGRAMMATIC REPRESENTATION OF FEMORAL HEAD NECK RATIO (SOURCE DOHERTY ET AL 2008 ²⁵⁵).....	299
FIGURE 60 FEMORAL HEAD RATIO (SOURCE DUDDA 2011)	300
FIGURE 61 THE IMPINGEMENT ANGLE (SOURCE DUDDA 2011).....	300
FIGURE 62 FEMORAL NECK ANTEVERSION (SOURCE SUTTER ET AL 2012 ⁴⁶).....	301
FIGURE 63 CROSS OVER SIGN.....	302
FIGURE 64 CENTRE EDGE ANGLE.....	303
FIGURE 65 TONNIS ANGLE	303
FIGURE 66 COXA PROFUNDA.....	304
FIGURE 67 ACETABULAR ANTEVERSION (SOURCE DANDACHLI ET AL 2010 ¹⁹⁹).....	305
FIGURE 68 ISCHIAL SPINE SIGN	305
FIGURE 69 POSTERIOR WALL SIGN.....	306
FIGURE 70 PROTRUSIO ACETABULI.....	306
FIGURE 71 ACETABULAR DEPTH (SORUCE PFIRMAN ET AL 2006 ¹⁶).....	307
FIGURE 72 SHARPS ANGLE.....	307
FIGURE 73 ANTERIOR ACETABULAR HEAD INDEX = (A/B)*100 (SOURCE CHOSA ET AL 2003 ³⁴⁴)	308

Acknowledgements

I would like to thank Professor D. Griffin, Professor C. Hutchinson and Doctor P. Wall who supervised me through my research degree. Without their ideas, guidance and support this thesis would not have been possible.

I would also like to thank those who have supported and collaborated with me during my various stages of work, they are:

Mr B. Robinson; for his help in conducting literature searches in chapter 2

Dr H. Parsons; for her advice regarding meta-analysis of data in chapter 2

Professor R. Buchbinder; for her guidance in conducting a systematic of epidemiological research

Dr J. O'Donnell; for his help in organising an international consensus meeting

Professor K. Bennell; for her help in organising an international consensus meeting

Mr L. Laver; for his help in assessing the inter rater reliability of measures in chapter 4

Dr M. Fernandez, for his help in organising and collecting data from professional golfers

Mr I. Ahmed, for helping collect data from professional golfers

Drs P. O'Connor, P. Robinson and R. Campbell in selecting and then reporting the MRI scans conducted in chapter 6.

Dr N Parsons; for advising on statistical matters throughout this thesis

Dr S. Wayte; for her help in designing MRI protocols for chapter 8.

Dr V. Sherwood for her help in designing and analysing MRI protocols in chapter 8.

Finally I would like to thank my father John for proof reading this thesis and my wife Nicola for her ongoing support during my PhD degree.

Declarations

This thesis is submitted to the University of Warwick in support of my application for the degree of Doctor of Philosophy. It has been composed by myself and has not been submitted in any previous application for any degree.

The work presented (including data generated and data analysis) was carried out by me except in the cases outlined below:

Chapter 2; Dr B Robinson provided an independent assessment for the search strategy and the identification of records.

Chapter 3: Professor D. Griffin, Dr J. O'Donnell and Professor K. Bennell aided in the identification and selection of consensus panel members.

Chapter 4: Dr. L. Laver repeated the radiographic measurements I recorded. Professor D. Griffin helped to develop the subtended acetabular edge angle measurements.

Chapter 6: Dr M. Fernandez and Dr I. Ahmed helped with the collection of data.

Chapter 8: Professor C. Hutchinson, Dr S. Wayte and Dr V. Sherwood designed the MRI protocols. Dr. V Sherwood advised on methods to conduct image analysis.

Publications

Part of this thesis have been published by the author:

1. Dickenson E, Wall PD, Robinson B, et al. Prevalence of Cam Hip Shape Morphology: A Systematic Review. *Osteoarthritis and Cartilage* 2016; 24 (6) 949-961
2. Dickenson E, Ahmed I, Fernandez M, et al. Professional golfers' hips: prevalence and predictors of hip pain with clinical and MR examinations. *British Journal of Sports Medicine* 2016; 50 (19) 1087-1091
3. Dickenson E, O'Connor P, Robinson P, et al. Hip morphology in elite golfers: asymmetry between lead and trail hips. *British Journal of Sports Medicine* 2016; 50 (17) 1081-1086
4. Griffin DR, Dickenson EJ, Agricola R, et al. The 2016 Warwick Agreement on Femoroacetabular Impingement. *British Journal of Sports Medicine* 2016; 50(19) 1169-1176.

5. Dickenson E, Ahmed I, Wall P, Laver L, Hutchinson C, Griffin D. A 3-Dimensional measure of acetabular morphology: Subtended edge angle (SEA). *submitted for publication*
6. Dickenson E, Wall P, Hutchinson C, Griffin D. The prevalence of cam hip morphology in the general population. *submitted for publication*

Presentations

1. Prevalence of Cam hip morphology; a systematic review. International Society of Hip Arthroscopy October 2014
2. Prevalence of Cam hip morphology; a systematic review. British Hip Society. 2015
3. Professional golfers' hips: prevalence and predictors of hip pain with clinical and MR examinations. British Association of Sports and Exercise Medicine. 2015
4. Hip morphology in elite golfers: asymmetry between lead and trail hips. British Association of Sports and Exercise Medicine. 2015
5. Definition and Epidemiology of Femoroacetabular Impingement. Sports Hip. June 2016
6. Femoroacetabular Impingement Syndrome. Royal College of Radiologists Annual Scientific Meeting. 2016.

Abstract

Femoroacetabular impingement syndrome is a disorder of the hip joint in which irregular contact occurs between the joint surfaces during motion, typically because certain hip shapes (cam or pincer morphology).

In this thesis a systematic review demonstrated that the point prevalence of cam and pincer morphology was not known. This systematic review identified that there were no established diagnostic criteria for cam and pincer morphology. A consensus development conference was used to define FAI syndrome and how it should be diagnosed. This consensus conference was unable to establish the radiographic criteria to define cam and pincer morphology. A case control diagnostic study was undertaken to identify the optimal measures to identify cam and pincer morphology, using cross sectional imaging. These definitions were applied to a sample representative of the general population in order to determine the point prevalence of cam and pincer morphology. The same diagnostic criteria were applied to a group of professional golfers, in this population, asymmetry between left and right hips, and cam and pincer morphology were found to be associated with reduced hip related quality of life.

A systematic review identified there was evidence to show that cam morphology caused hip osteoarthritis. However, the evidence to show that pincer morphology and FAI syndrome caused OA was presently lacking. No experimental studies were identified assessing whether treating cam and pincer morphology or FAI syndrome altered the risk of developing OA. A feasibility randomised controlled trial was conducted to determine whether proxy markers of osteoarthritis, measured on magnetic resonance imaging, could be used in a trial to determine whether surgery alters the natural history of FAI syndrome.

Word count: 269/300

Abbreviations

AMED	Allied and Complementary Medicine Database
AUC	Area under the curve
BR	Ben Robinson
CEA	Centre Edge Angle of Wiberg
CH	Charles Hutchinson
CI	Confidence Interval
CT	Computed Tomography
CINAHL	Cumulative Index to Nursing and Allied Health
CONSORT	Consolidated Standards of Reporting Trials
DG	Damian Griffin
dGEMRIC	Delayed Gadolinium Enhanced Magnetic Resonance Imaging of Cartilage
DICOM	Digital Imaging and Communication File
EMBASE	Excerpta Medica Database
FABER	Flexion abduction external rotation
FADIR	Flexion adduction internal rotation
FAI	Femoroacetabular Impingement
FASHIoN	Full trial of Arthroscopic Surgery for Hip Impingement compared with best conservative care
GAG	Glycosamino Glycan
GRE	Gradient Echo
HOAMS	Hip Osteoarthritis Magnetic Resonance Scoring System
HP	Helen Parsons
HTA	Health Technology Assessment Programme
IA	Imran Ahmed
ICRS	International Cartilage Repair Society
IHOT-33/12	International Hip Outcome Tool – 33/12
IMD	Index of multiple deprivation
IR90	Internal rotation in 90 degrees of flexion
ISRCTN	International Standard Randomised Controlled Trial Number Register
IQR	Inter Quartile Range
KL	Kellgren Lawrence
LL	Lior Laver
MF	Miguel Fernandez
MPR	Multi-planar reformatting
MR	Magnetic resonance
MRC	Medical Research Council
MRI	Magnetic resonance imaging
n/a	Not applicable
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
NIHR	National Institute of Health Research
OA	Osteoarthritis
PHT	Personalised Hip Therapy
POC	Philip O'Connor
PR	Philip Robinson
PW	Peter Wall
SD	Standard Deviation
SEA	Subtended Edge Angle
SPGR	Spoiled gradient echo
SW	Sarah Wayte
RC	Robert Campbell
ROC	Receiver operator characteristics
ROI	Region of Interest
RCT	Randomised Controlled Trial
T	Tesla
TAL	Transverse Acetabular Ligament
TE	Echo Time
TFL	Tensor fascia lata
THR	Total hip replacement
TR	Relaxation Time
UHCW	University Hospital Coventry and Warwickshire
UK	United Kingdom
VS	Victoria Sherwood
3D	Three dimensional
α	Alpha

Research Training

Courses Attended

1. Chief Investigators Course. University of Warwick 2018
2. Postgraduate certificate in Transferable Skills. University of Warwick 2017
3. Introduction to Regression. Centre for applied statistics UCL. 2017
4. Business Innovation and Commercialisation for Researchers. University of Warwick. 2017
5. Decision-making and leadership. University of Warwick. 2017
6. Site builder Training. University of Warwick. 2017
7. Science Communication. University of Warwick. 2016
8. Case Based Learning Facilitator Training. University of Warwick. 2016
9. Understanding research and critical appraisal in health care course. University of Warwick. 2015
10. Design, analysis and interpretation of epidemiological research. University of Warwick. 2015
11. Research ethics and governance training. University of Warwick. 2014
12. NIHR Introduction to Good Clinical Practice. University of Warwick. 2014

Conferences Attended

1. International Society of Hip Arthroscopy 2014
2. International Society of Hip Arthroscopy 2015
3. British Hip Society 2015
4. British Orthopaedic Association 2015
5. Sports Hip 2016
6. Royal College of Radiologists Annual Scientific Meeting 2016
7. International Clinical Trials Methodology Conference 2017
8. British Orthopaedic Association 2017

1 Introduction

In this chapter, I provide an overview of hip anatomy and relevant hip joint pathology in order to set the remainder of the thesis in context. I shall provide a summary of hip anatomy, the structure of the articular cartilage and describe hip osteoarthritis. I give an overview of femoroacetabular impingement syndrome that will allow me to explore certain aspects of the disorder in the remainder of the thesis.

1.1 Background

The hip joint is traditionally viewed in simplistic terms; it is a stable ball and socket joint and is only affected by a limited number of disorders such as osteoarthritis (OA), slipped upper femoral epiphysis (SUFE), Legg Calve Perthes disease and developmental dysplasia of the hip (DDH).^{1,2} However this does not take account of the subtleties of hip anatomy or the functional requirements, both of which may predispose to pathology.

Smith-Peterson first introduced the concept of hip impingement in 1936.³ It took until 2003 for Ganz et al to describe femoroacetabular impingement (FAI), its management and how it is a potential cause of hip osteoarthritis.⁴ This led to a popularisation of the concept. Over the last decade, the number of patients being diagnosed and treated has continued to rise.⁵⁻⁷

In chapter 3 of this thesis, we introduce the term *FAI syndrome*. This was designed to place an emphasis on patients with symptoms when discussing the disease.

The popularisation of FAI syndrome requires us to re-evaluate the hip joint from a new perspective. We need to understand how to define FAI syndrome, describe its epidemiology and scrutinise its association with hip OA. In order to do this I shall first describe the hip anatomy and the present understanding of hip OA and FAI syndrome.

1.2 Hip Anatomy and Function

I shall consider the hip anatomy using the four layered approach, which was initially developed by the MAHORN (multicentre arthroscopy of the hip outcome research network) group in relation to clinical examination of the hip.⁸

1.2.1 Bony Anatomy

Femoral Anatomy

The proximal femur has a unique morphology that has evolved to support the functional requirements of the hip. Femoral neck antetorsion refers to the rotation of the femoral neck in the axial plane, relative to the distal femoral condyles; see appendix (section 11).⁹ The femoral neck is typically angled anteriorly relative to the distal femoral condyles by 10° (SD 9), this is called the femoral neck antetorsion.⁹ The femoral neck shaft angle is a coronal plane feature of the proximal femur. It describes the angle at which the femoral neck projects medially relative to the long axis of the femur; see Appendix (section 11).¹⁰ The neck shaft angle is typically 129° (SD 7) in males and 133° (SD7) in females.¹⁰

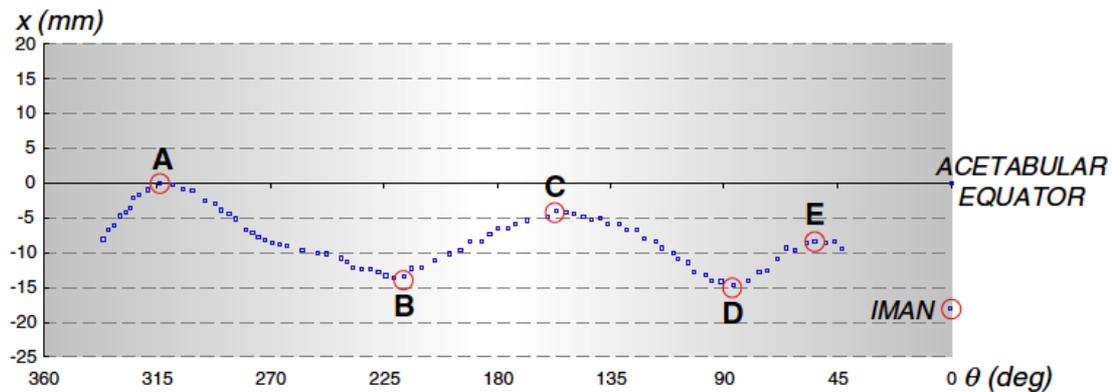
Despite being referred as the “ball”, the femoral head is not spherical but spheroidal (slightly oval) in shape.¹ In evolutionary terms mammals display two different forms of femoral head and neck. The coxa recta hip displays a flattening of the femoral head with reduced offset between the head and neck, and an associated shallow acetabulum.¹¹ This is a common shape in sprinting mammals.¹¹ The coxa rotunda is a round femoral head with a high offset neck, associated with deep acetabulum.¹¹ This morphology is a feature of apes and swimming mammals.¹¹ Both of these evolutionary hip morphologies are apparent in humans and affect the roundness of the femoral head, head neck offset and acetabular depth. The femoral head neck offset describes the ratio between the width of the femoral head and the femoral neck (see appendix).¹² A large round head with a narrow neck will have a high offset, whereas a broad neck on a smaller head will have lower offset. The relevance of these shapes with respect to pathology are discussed in more detail later in the introduction.

The femoral head derives its blood supply from branches of the profunda femoral artery. The profunda femoral artery branches to give the medial and lateral femoral circumflex arteries. The medial circumflex artery passes medial and posterior to the femur. It has 5 terminal branches. The deep terminal branch emerges in the deep gluteal space between obturator externus and quadratus femoris. It gives 2-4 retinacular branches that ascend the posterior aspect of femoral neck deep to the synovium. They perforate the bone 2-4mm distal to the femoral head neck junction.

Acetabular Anatomy

The acetabulum is a concave surface located on the lateral aspect of the pelvis. It is composed of the acetabular lunate; a 'C' shape articular surface, and the cotyloid fossa which possesses a central and inferior depression.¹ The cotyloid fossa is filled with fibroelastic fat and covered with a synovial membrane.¹ The acetabular rim is not smooth but undulating, see Figure 1.¹³ A groove to allow the smooth passage of the iliopsoas tendon forms on the anterosuperior border of the acetabulum; this depression in the rim has been called the psoas notch or iliopubic trough.^{13,14} A further trough is found inferiorly in the form of the cotyloid fossa notch, and postero-superiorly called the ilioischial trough.¹⁵ Peaks along the acetabular rim have been described at the pubic eminence, iliac eminence and ischial eminence (E, C and A respectively in Figure 1).¹⁵ The normal acetabulum is slightly less than hemispherical in depth relative to the size of the femoral head, which sits within it. The depth of the acetabulum can be determined by measuring the perpendicular distance from the centre of the femoral head to a line drawn from the anterior to the posterior acetabular rim.¹⁶ This is measured at the level of the mid point of the femoral head on axial oblique imaging, a normal depth is 5mm at this level.¹⁶

Figure 1 Acetabular rim demonstrating undulating profile. A ischial eminence B ilioischial trough C iliac eminence D iliopubic trough E pubic eminence IMAN inferior margin of acetabular notch. Source Vandendussch et al ¹⁵

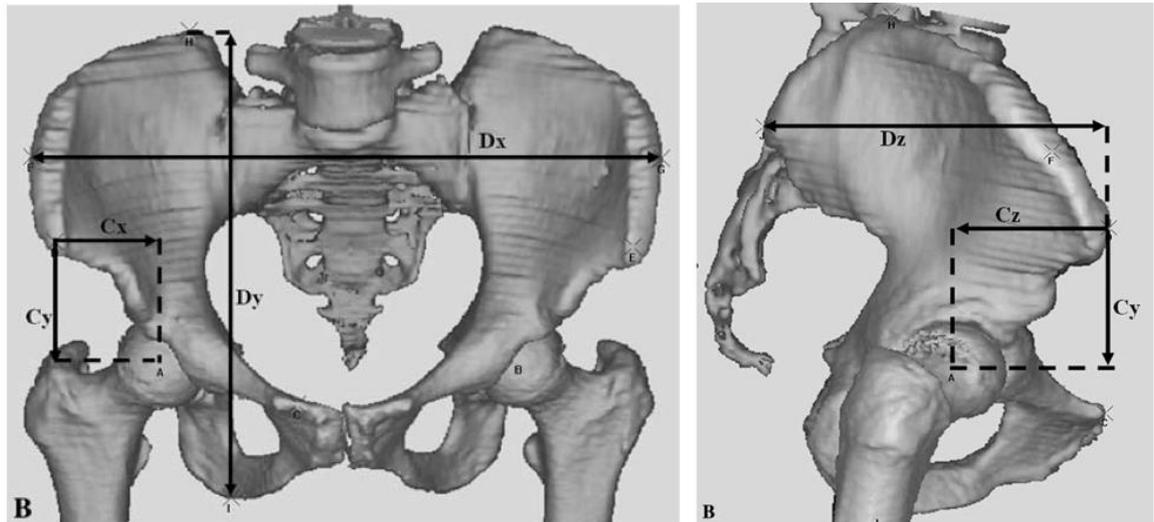


The acetabular blood supply is derived from complex, variable anastomosis of the obturator artery, superior and inferior gluteal arteries, lumbar artery and iliolumbar artery. ¹⁷ The superior aspect of the acetabulum is predominantly supplied by the acetabular ramus and supra-acetabular ramus; divisions of the deep branch of the superior gluteal artery. ¹⁷ The acetabular branch of the inferior gluteal artery supplies the postero-inferior aspect of the acetabulum. ¹⁷ The inferior aspect, is supplied by the acetabular branch of the obturator artery.¹⁷

Pelvic Anatomy

The acetabulum resides on the anterolateral aspect of the pelvis, and is orientated to antero-inferiorly. The precise location of the centre of the acetabulum can be determined from antero superior iliac spine (ASIS) using ratios of the width, depth and the height of the pelvis; see Figure 2.¹⁸ This position differs slightly in males and females. In its location the acetabulum is anteverted. This term refers to the anterior orientation of the acetabular opening in the axial plane.¹⁹ The acetabulum is typically anteverted by 17°. ¹⁵ The acetabulum is also inclined. The acetabular inclination refers to the inferolateral projection of the acetabular opening in the coronal plane.¹⁹ It has an inclination of approximately 39°. ¹⁵ Anteversion and inclination are measured relative to the anterior pelvic plane (APP). The APP is formed between the right and left ASIS and the right and left pubic tubercles.¹⁵

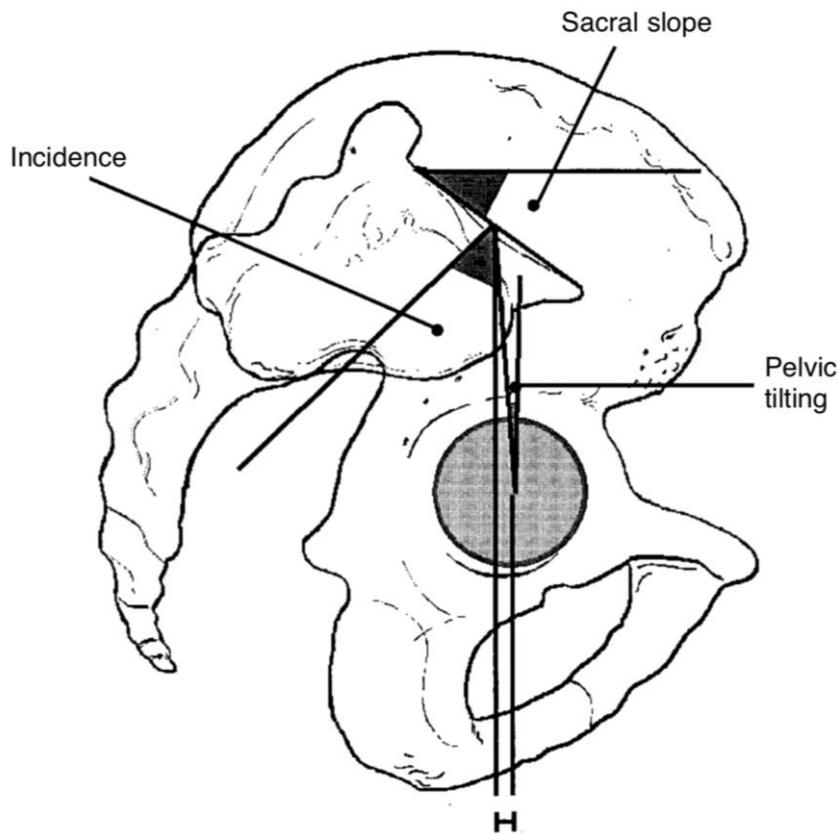
Figure 2 Position of the acetabulum within the pelvis, determined from the ASIS. The Cx:Dx in males is 10% and 8% in females. The Cy:Dy is 36% in amels and 32% in females and the Cz:Dz is 39% in males and 36% in females. Source Dandachli et al ¹⁸



Spine Hip Relations

The relationship between the pelvis and spine affects the ability for the pelvis to tilt and roll in the sagittal plane.²⁰ This movement contributes to the functional position of the acetabulum, and changes during different tasks such as lying supine, sitting and standing.^{20,58} This relationship, called the spine hip relationship, is defined by the pelvic incidence, sacral slope and pelvic tilt; see Figure 3.²¹ Pelvic incidence is the angle measured on a lateral pelvic radiograph between the centre of the femoral head, and a line perpendicular to the sacral endplate.²¹ The pelvic tilt refers to the sagittal orientation of the pelvis, using the anterior pelvic plane as a reference.²² It is measured as the angle between the line connecting the midpoint of the sacral plate to the axis of the femoral heads, and the vertical axis of the anterior pelvic plane. The sacral slope is the angle between the horizontal plane and the sacral endplate.²³ The pelvic tilt and sacral slope are inversely proportional.²²

Figure 3 Diagram of the lateral view of the pelvis showing the pelvic incidence, sacral slope and pelvic tilt. Source Legaye et al ²¹



1.2.2 Hyaline Cartilage

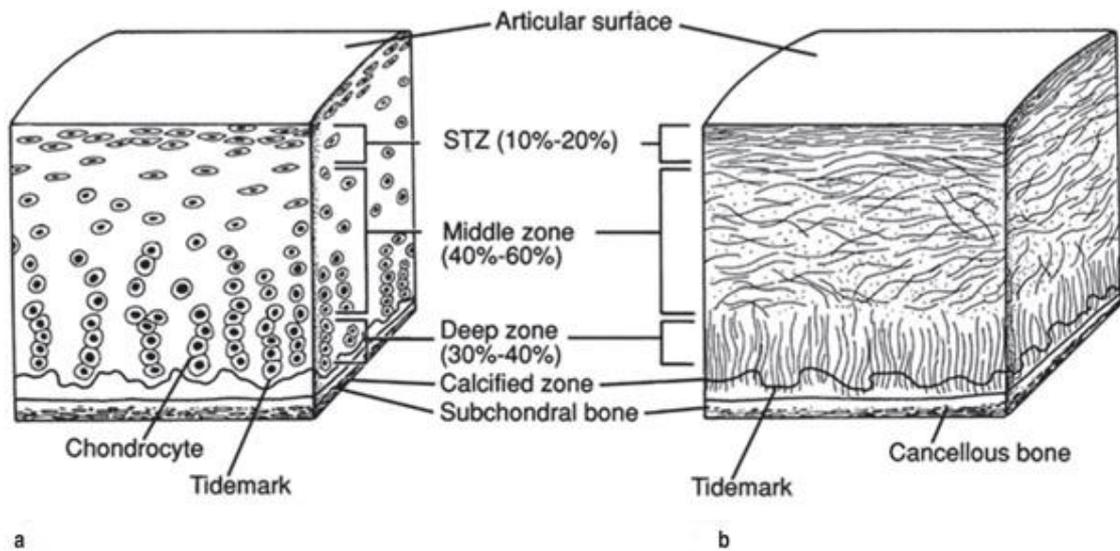
The articular surfaces of the femoral head and acetabulum are covered in hyaline cartilage. Hyaline cartilage offers a low friction and highly resilient articular surface. Hyaline cartilage consists of chondrocytes and the extra cellular matrix that they synthesise.²⁴ Once mature, chondrocytes reside in lacunae and represent only 1% of the cartilage weight.²⁵ From here chondrocytes synthesise and secrete the extracellular matrix which includes collagen, proteoglycans, non collagenous proteins, glycoproteins, water and cations.²⁴ Water makes up 60% of the mass of hyaline cartilage.²⁵ Collagen forms 60% of the dry weight of cartilage, of which 95% is type 2 collagen. Types VI, IX, X and XI are also present in small quantities.²⁵ Proteoglycans within hyaline cartilage are divided into three groups; large aggregating proteoglycans, small proteoglycans and large non aggregating proteoglycans. Proteoglycans form 25-35% of the dry mass of hyaline cartilage. The large aggregating proteoglycans are formed of a core protein with glycosaminoglycan (GAG) side chains.²⁴ The large aggregating proteoglycans are

linked to chains of hyaluronic acid via link proteins and non covalent bonds. GAGs are negatively charged drawing cations, which increases the osmolarity of cartilage therefore retaining a high content of matrix water. The cartilage acts as a biomechanical spring, water is forced out of the cartilage matrix and into the synovial fluid during loading, and back when the joint is unloaded.²⁴ This function allows the synovial fluid to nourish the chondrocytes.

Hyaline cartilage can be divided into four distinct zones; superficial, transitional (or middle), radial (or deep) and calcified cartilage (see Figure 4).¹ The superficial zone contains the highest concentration of collagen fibres and relatively few chondrocytes. Collagen fibres and oval chondrocytes are arranged parallel to the articular surface to resist shear forces. In the transitional zone the collagen fibres and oval chondrocytes are more obliquely orientated allowing them to transmit load. In the radial zone the collagen fibres and the large round chondrocytes are arranged radially to resist compression. The calcified cartilage is a thin zone of small cells in a calcified matrix that separates the radial zone and the subchondral bone.¹

A further microstructure exists within hyaline cartilage delineated by the distance from the chondrocytes. Adjacent to each lacuna is a peri-cellular zone that is rich in proteoglycan and contains cytoplasmic extensions. Adjacent to this zone is the territorial zone that contains thin collagen fibrils that adhere to the peri-cellular matrix. The inter-territorial zone is made of large diameter collagen fibrils that are orientated according to their relative depth in the cartilage.²⁵

4 Cross sectional diagram of hyaline cartilage. Source Steward 2011 ²⁶ (a) Chondrocyte and (b) collagen fibre organisation in articular cartilage STZ: superficial transitional zone



1.2.3 Hip Labrum and Capsule

The primary stability of the hip is generated by the congruence of the articular surfaces. In order to maintain stability through a range of movements a number of soft tissue structures provide secondary stability. The ligamentum teres is flattened band that is taught in flexion, adduction and external rotation. It originates in the fovea of the femoral head and inserts at the base of the cotyloid fossa blending with the transverse acetabular ligament (TAL).¹

Attached to the rim of the acetabulum is the labrum. The labrum is a fibrocartilage structure that is triangular in cross section.²⁷ The labrum's base is attached to the acetabular rim. The internal surface of the labrum forms a smooth transition with hyaline cartilage and its free edge projects over the femoral head.^{27,28} Inferiorly the labrum attaches to the TAL, which crosses the cotyloid fossa's notch. The labrum has a number of functions:

- Deepens the hip joint by projecting lateral to acetabular rim
- Provide secondary stability by generating suction seal
- Indirectly aids the nourishment of the articular cartilage by containing synovial fluid in the intra articular space.^{28,29}

The hip is encased by the joint capsule; a strong dense fibrous structure. It originates above the acetabular margin, just medial to the labrum and inserts at the base of the femoral neck.¹ There are three distinct thickenings of the capsule: the iliofemoral, the ischiofemoral and the pubofemoral ligaments.¹ These three ligaments provide secondary stability to the hip joint.

1.2.4 Hip Musculature

As the hip is a relatively deep joint it is also surrounded by muscles. These muscles confer additional stability and facilitate movement. Movements can occur in the sagittal, coronal and axial planes. The range of movement is typically influenced by muscular balance, the joint capsule and hip bony morphology.

Hip flexion can occur from 0° to between 100-135°.³⁰ Flexion is primarily facilitated by the psoas, iliacus and rectus femoris, which are assisted by pectineus, tensor fascia lata (TFL) and sartorius.¹ Psoas originates from the transverse processes of the lumbar vertebrae and inserts in the lesser trochanter.¹ The iliopsoas tendon crosses the hip joint anteriorly forming the psoas notch on the anterior acetabular margin.¹

Extension of the hip occurs from 0° to between 15° and 30°.³⁰ It is facilitated by the activation of gluteus maximus, adductor magnus and the hamstrings: biceps femoris, semimembranosus and semitendinosus.¹ Abduction typically occurs from 0° to between 40° and 45°.³⁰ The abductors function is facilitated by the gluteus medius and minimus which are assisted by TFL, piriformis and sartorius.¹ Hip adduction can occur up to 25°.³⁰ The main hip adductors are the adductor longus, brevis and magnus, and gracilis which are assisted by pectineus and quadratus femoris.¹ The range of hip internal rotation in extension is from 0° to 40°.³⁰ The anterior fibers of gluteus medius and minimus, pectineus, TFL and all the adductors internally rotate the hip.¹ External hip rotation of up to 40° is facilitated by gluteus maximus and the short external rotators: piriformis, superior and inferior gemelli, obturator internus, obturator externus, quadratus femoris.^{1,30}

In simplistic terms the centre of the femoral head is considered to act as a fixed fulcrum around which the hip rotates.¹ However, movement does not always occur in this way. As well as rotating around the fulcrum of rotation, the hip is also translates and slides within the acetabulum.³¹ In certain circumstances, at the limit of movement, the head can lever out of the acetabulum.^{32,33}

1.3 Hip Pathology

Although a number of disorders can affect the hip joint, for the purpose of the introduction to this thesis I shall only describe OA and FAI syndrome.

1.3.1 Osteoarthritis

Definition

OA is a disorder of synovial joints. It is defined as a clinical syndrome of joint pain, functional limitations (such as stiffness) and a reduced quality of life.^{34,35}

In the hip, OA is diagnosed by the presence of hip pain most days of the previous month, and two of the following features:

- Radiographic femoral or acetabular osteophytes
- Radiographic joint space narrowing
- Erythrocyte sedimentation rate <20mm/hour.³⁶

Radiological Signs

Radiographic signs of osteoarthritis include joint space narrowing, osteophyte formation, bone cysts and subchondral sclerosis.³⁷ Several radiographic grading systems have been proposed. The Kellgren and Lawrence (KL) system is used to grade OA in all joints, it consists of a scale of 0-4.³⁸ The Tonnis systems is hip specific and has 4 grades:

- Grade 0- No sign of OA,
- Grade 1- Slight narrowing of joint space, slight lipping at joint margin, slight sclerosis of femoral head or acetabulum,
- Grade 2- Small cysts in femoral head or acetabulum, increasing narrowing of joint space, moderate loss of sphericity of femoral head,

- Grade 3- Large cyst, severe narrowing or obliteration of joint space, severe deformity of femoral head, avascular necrosis.³⁹

Epidemiology

When measuring the incidence and prevalence of hip osteoarthritis it is important to understand the relationship between radiographic findings and the syndrome of OA. Radiographic signs of OA are often present in the absence of symptoms, while symptoms are often disproportional to the amount of degenerative changes noted on plain radiographs.³⁷ The prevalence of both radiographic OA and hip OA syndrome is known to increase with age.⁴⁰

Radiographic hip OA is identifiable in 11% of adults over 50 years, while the prevalence of hip OA syndrome is 5%.³⁴ The standardised (by age and sex) incidence of hip OA is 88 (95% confidence interval [CI] 75-101) per 100,000 person years.⁴⁰ In England, Wales and Northern Ireland in 2016 88,000 primary total hip replacements (THR) were performed, 92% of which were for OA.⁴¹

Pathogenesis

OA is a metabolically active disorder that involves all components of synovial joints. There is a pathological loss of hyaline cartilage, remodeling of subchondral bone, formation of marginal osteophytes, synovial inflammation, capsular thickening and weakness of periarticular muscles.^{34,37,42}

It has been suggested that osteoarthritis is not a single disease but multiple disorders with a final common pathway.⁴³ Supporting this theory are the various risk factors associated with OA in different joints, the presence of polyarticular versus monoarticular OA, the differing classifications of OA (primary vs secondary OA) and the different pathological processes observed (e.g. hypertrophic vs atrophic hip OA).⁴³ Consequently, in order to understand the disease, various risk factors must be considered.

Risk Factors

Dieppe proposed a model for the development of OA that consisted of a number of risk factors; see Figure 5.⁴⁴ Table 1 describes the general and local biomechanical risk factors associated with hip joint OA.³⁷

Figure 5 Pathogenesis of Osteoarthritis adapted from Dieppe. The classification and diagnosis of osteoarthritis 1995⁴⁴

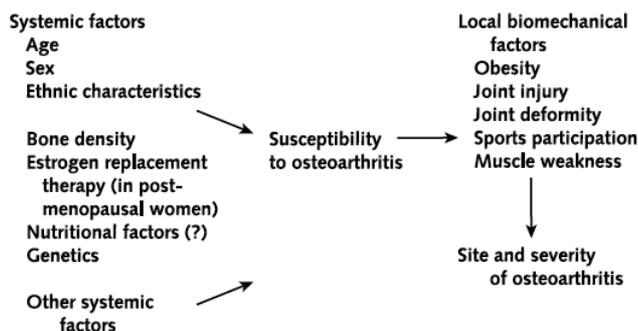


Table 1 Risk Factors for Hip OA³⁷

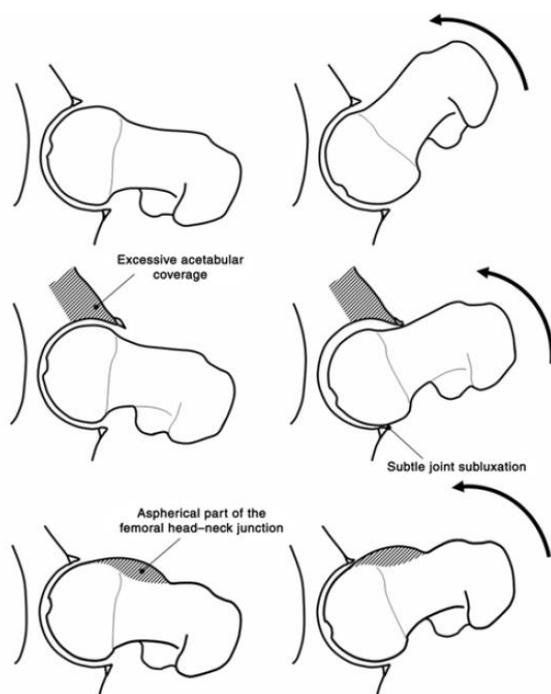
Systemic risk factors		Local biomechanical factors	
Age	Increasing age associated with OA	Obesity	Risk factor for THR, less strong association than in knee OA
Gender	Hip OA frequency similar between males and females. Progress faster in females.	Acute Injury	Acute injury and trauma are risks for OA.
Sex Hormones	Rise in incidence of OA in post menopausal women, this is reduced in subjects on HRT.	Repetitive activity	Moderate recreational activity without injury not associated with OA. Professional athletes without injury are associated with OA.
Bone density	Higher bone mineral density observed in subjects with OA.	Joint Deformity	Strong association between deformities such as slipped femoral epiphysis and hip dysplasia and OA.
Ethnicity	Black Africans, Afrocaribbeans and Chinese have reduced rates of hip OA compared to white Caucasians		
Genetics	Half of population variability in OA explained by genetics. Multiple genes implicated		

1.3.2 Femoroacetabular Impingement Syndrome

FAI syndrome is a condition characterised by hip pain, caused by an abnormal premature contact between the proximal femur and the acetabulum.⁴ This abnormal contact, or impingement, occurs as a result of hip motion in the presence of characteristic hip shapes.⁴ A 'cam hip shape' is an asphericity of the femoral head at the femoral head neck junction; see Figure 6.⁴ The word cam originates in

engineering; where a cam is a projection on a rotating machine that is designed to make periodic contact during motion e.g. cam shaft in the combustion engine. Pincer morphology is a global or focal over coverage of the femoral head by the acetabulum; see Figure 6.⁴

Figure 6 Normal configuration of hip with sufficient joint clearance to allow unrestricted range of motion (top). In pincer impingement acetabular over coverage leads to early contact between the femoral head neck junction and acetabular rim (middle). In cam impingement the aspherical aspect of femoral head neck junction intrudes into the acetabulum during motion; typically flexion and internal rotation (bottom). Source Tannast et al 2007.⁴⁵



Impingement occurs during hip motion when cam or pincer hip shapes cause an abnormal, premature contact of the joint surfaces.³² Other hip shapes that are associated with FAI syndrome include low femoral neck shaft angle and low femoral neck antetorsion.⁴⁶ Impingement can also occur in the absence of these hip shapes in patients with a supra-physiological range of motion, for example ballet dancers.⁴

The concept of FAI syndrome was popularised by Ganz et al, who in 2001 described a surgical hip dislocation which preserved the blood supply to the femoral head. In 2003 Ganz et al proposed that FAI syndrome was a cause of hip osteoarthritis.^{4,47} The role of certain hip shapes in osteoarthritis was also recognised by Murray (1965), Stulberg et al (1975) and Harris (1986) who described abnormalities of the

proximal femoral and acetabular shape that may account for hip osteoarthritis previously deemed idiopathic.⁴⁸⁻⁵⁰ Harris's description of the proximal femoral '*pistol grip deformity*' would latterly be recognised by Ganz et al as cam morphology.⁵⁰

As our understanding of FAI syndrome has evolved other forms of pathoanatomy and movement disorders have been described and associated with the FAI syndrome. These include factors outside the hip joint such as a reduced femoral neck antetorsion.³⁹ A low femoral neck antetorsion reduces the functional amount of hip internal rotation, therefore increasing the likelihood of anterior impingement.⁴⁶

More recently a focus on the role of spine hip relations has led to new theories about the development of FAI syndrome. It has been hypothesised that a reduced pelvic incidence may contribute to the development FAI syndrome in patients with cam or pincer morphology, due to a loss in the ability of the pelvis to posteriorly tilt.^{51,52} This is supported by a number of studies in gait laboratories have demonstrated that subjects with FAI syndrome have reduced sagittal pelvic range of motion.⁵³⁻⁵⁶ Lamontagne et al showed that in a deep squat subjects with FAI syndrome had reduced posterior pelvic tilt.^{55,57}

Poor hip and core muscular function is also a potential cause of FAI syndrome. In subjects with FAI syndrome static hip strength and functional control (e.g. single knee dip balance) are reduced.¹⁵⁷ What is unclear is whether deficits in this muscular control contributed to the development of FAI syndrome, or is a consequence of the disorder. Loss of muscular control may allow the hip to move into positions that make it prone to impinging.

Radiological Assessment

Antero-posterior (AP) pelvic radiographs are helpful in obtaining an overview of the hips, however it is challenging to interpret the three-dimensional anatomy from an AP radiograph alone. In these circumstances a lateral femoral neck view can augment an AP radiograph. A number of different lateral femoral neck views have been described including the cross table, 90° Dunn, 45° Dunn and frog laterals.⁵⁸ The

cross table lateral radiograph is taken with the patient supine, their contralateral hip and knee flexed and the symptomatic hip internally rotated.¹² The x-ray beam is focused at 45° angle to the ipsi-lateral leg, parallel with the table.¹² The 90° and 45° Dunn lateral are taken with the patient supine, with their hips flexed 90° and 45° respectively, with 20° of abduction and neutral rotation.⁵⁹ The x-ray beam is focused on the hip anteriorly, in an AP plane to the pelvis.^{58,59} The frog lateral radiograph is taken with the patient supine on the x-ray table with their hips flexed 40° and abducted 45°.⁶⁰ The x-ray beam is focused anteriorly on the hip in an AP direction.⁵⁹ While all of these views assess the anterior aspect of the head neck junction in slightly different planes, to truly appreciate the 3D anatomy cross sectional imaging is required.

Computerised tomography (CT) allows 3D reformatting, which enables reconstruction of the images in multiple different planes.⁶¹ Volume rendering of CT allows a qualitative interpretation of the anatomy. CT or MR imaging with axial cuts of the knees, allows femoral neck antetorsion to be determined.

Magnetic resonance (MR) imaging may be non contrast or contrast enhanced (MR arthrogram). MR imaging is performed in a number of different planes, typically axial oblique (oblique to the line of the femoral neck), coronal and sagittal. MR imaging is used to assess the soft tissue component such as labral tears and the articular cartilage.⁶¹

Radiological Signs

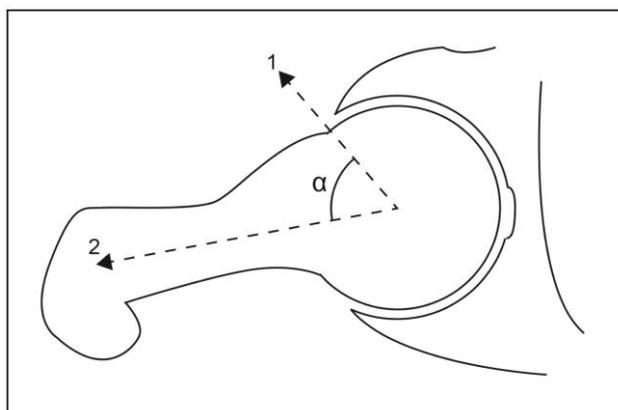
Radiographic signs of FAI syndrome include the presence of cam and pincer hip shapes, and evidence of intra articular injuries, such as labral tears.

An AP radiograph provides a simple initial assessment of the hips. An AP radiograph should be centred on the pubic symphysis without rotation and with neutral pelvic tilt.⁴⁵ An AP radiograph can be used to gain an overview of the hips assessing the presence of other causes of hip pain such as OA.⁶¹

The presence of cam morphology can be made by a qualitative assessment of the presence of cam morphology.⁵⁰ A number of quantitative measures of cam morphology have since been described. An overview of these can be found in the Appendix (Section 11.1). The most frequently encountered is the alpha (α) angle.⁶² In 2002 Notzli et al described the α angle as a measure of the anterior femoral head neck junction made on axial oblique MR imaging.⁶² The α angle has since been adapted and used to quantitatively assess for the presence of cam hip shape. It is a measure of the angle between the mid axis of the femoral neck and centre of the head, and the centre of the femoral head and the position on the anterior head neck junction where the radius of the head is exceeded; see Figure 7.⁶² Other measures of cam morphology include the Triangular index described by Gosvig et al,⁶³ the head neck offset described by Eijer et al,¹² and the pistol grip deformity described by Stulberg (see appendix).⁴⁹

Other measures of proximal femoral morphology associated with FAI are the presence of coxa vara and femoral neck retrotorsion; see Appendix (Section 11.1).⁵⁸

Figure 7 Diagrammatic representation of how to measure an alpha angle. Source Notzli et al 2002 ⁶²



The radiographic assessment of pincer morphology involves establishing the presence of global and focal over coverage.⁶¹ Global over coverage is noted by the presence of coxa profunda, acetabular protrusio, an increased Centre Edge Angle of Wiberg or a reduced acetabular inclination.^{64,65} Focal overcoverage can be identified on an AP radiograph by the presence of a cross over sign.⁶⁶ Numerous

different measures of pincer morphology have been defined and these are described in the Appendix (Section 11.1).

Assessing pincer morphology presents something of a diagnostic challenge to surgeons. Early case series reported that a large number of patients had combined cam and pincer morphology.^{68,69} This is contradictory to the understanding of the evolution of the mammal hips, which suggests cam and pincer morphology are distinct entities not observed together.¹¹ This theory is supported by research evaluating cam hips showing their acetabulum were shallower than controls and did not show signs of pincer morphology.¹⁴ This conflicts with case series that report large numbers of patients with FAI syndrome having combined bone-resecting surgery for cam and pincer impingement.^{68,69} This suggests a controversy in how cam and pincer morphology are being diagnosed; I shall explore this in chapter 4.

Mechanism of Injury

Ganz et al, and later Beck et al, proposed that cam and pincer type FAI syndrome caused distinct injury patterns that resulted in hip OA.^{4,32}

The jamming into the acetabulum of a cam hip shape during motion was suggested to result in shear forces that produced an outside-inside abrasion of the labrum and acetabular cartilage. This resulted in labral tears and delaminating the cartilage from the subchondral bone.^{4,32}

During motion the presence of pincer morphology was proposed to cause an abutment of the femoral neck with the acetabular rim. It was proposed that over time this recurrent abutment caused labral degeneration and ossification, further deepening the acetabulum. Persistent abutment was suggested to cause the femoral head to lever out of the acetabulum resulting in a contrecoup injury to the acetabular cartilage; see Figure 6.^{4,32}

Treatment

Treatments for FAI syndrome include conservative care, physiotherapy led rehabilitation and arthroscopic or open surgery.⁷⁰

Conservative care is typically offered in a primary care setting to patients with mild symptoms. It includes the clinician offering education and advice about FAI syndrome that may result in activity modification and administering simple analgesics. Watchful waiting may be used to monitor symptoms and active treatments could be considered should symptoms deteriorate.^{70,71}

Physiotherapy led rehabilitation aims to reduce patients symptoms by improving hip neuromuscular control and correcting abnormal movement patterns.⁷¹⁻⁷⁵ The justification for physiotherapy is the findings of abnormal movement patterns, such as reduced sagittal and frontal plane hip range of motion, and weakness of certain muscle groups, such as hip flexors, adductors, external rotators and abductors.^{72,76} These provide treatment targets for physiotherapists. A package of physiotherapist led best conservative care called personalised hip therapy (PHT) was designed to specifically treat FAI syndrome.⁷⁴

The surgical treatment of FAI syndrome aims to alter the hip joint shape and repair damaged tissue thereby promoting impingement free motion. Surgical approaches depend on the degree of correction desired. Surgery may be open; either a surgical hip dislocation, rotational femoral osteotomies or reverse peri-acetabular osteotomy, or arthroscopic.^{47,77-79}

The effectiveness of these treatments is currently being assessed by a number of randomised controlled trials (RCT)(trial registrations: ISRCTN64081839, ACTRN12615001177549, NCT01893034, NCT01623843, NCT02692807, NCT01993615), including the UK FASHIoN trial. During my PhD I have worked as the clinical research fellow delivering the UK FASHIoN trial, a multicentre study assessing the clinical effectiveness of hip arthroscopy versus physiotherapy led rehabilitation in patients with FAI syndrome.⁸⁰ This research post follows the successful FASHIoN feasibility study conducted by my supervisors.⁷ The FASHIoN feasibility study formed part of my predecessors PhD thesis. My thesis aims to build on the work conducted by Peter Wall in his thesis “Treatments for Femoroacetabular Impingement” completed in 2014.⁸¹

1.4 Thesis Aims and Objective

Having only been described and popularised in 2003, our understanding of FAI is still in its infancy. Despite a year on year increase in the number of relevant publications many questions remain about the causes, epidemiology, optimal treatment and the long term outcomes of FAI syndrome. Associated with the increase in publications potentially confusing term such as '*asymptomatic FAI*' and '*radiographic FAI*' have also emerged which I believe are misleading and confusing.^{82,83}

Over the last decade there has also been a large increase in the number of patients being diagnosed and treated for FAI syndrome.⁵⁻⁷ With such a rapid increase in diagnosis and treatment one has to consider the possibility that FAI syndrome is being over diagnosed, especially as some fundamental aspects of the epidemiology remain unanswered.⁸⁴

In order to prevent over diagnosis and over treatment an unambiguous definition of FAI syndrome is required, with clear diagnostic criteria including relevant imaging findings. This will allow the epidemiology and natural history of the disorder to be defined.

A further emerging theme in FAI syndrome, which I have observed at International Meetings (International Society of Hip Arthroscopy annual meeting Rio de Janeiro 2014 and Cambridge 2015), is the strength of feeling that FAI syndrome is a *cause* of OA. Some surgeons make bold statements that with surgery treatment it is a preventable cause! These statements concern me. Confusion seems to have developed in the surgical community about the concept of causality. Is it FAI, the clinical syndrome that is considered the *cause* of OA. Or are the hip shapes, particularly cam morphology, in the absence of symptoms the cause of OA? The natural history of the condition needs to be understood before we can scrutinise whether treatment alters that association.

In order to make a positive contribution to the growing body of literature I chose to explore the epidemiology of FAI syndrome.

The aims of this thesis are to:

- Systematically review the current epidemiological evidence to determine the prevalence of cam and pincer morphology.
- Define FAI syndrome, its diagnostic criteria and how cam and pincer morphology should be measured, describing the diagnostic utility of those measurements.
- Establish the prevalence of cam and pincer morphology in the general population and in a population of elite athletes.
- Systematically review the evidence that demonstrates whether FAI syndrome causes hip OA.
- Evaluate a method to assess changes in surrogate markers of hip OA in the setting of a randomised controlled trial.

2 What is the prevalence of cam and pincer hip morphology; a systematic review

In this chapter, I present a systematic review of the prevalence of cam and pincer morphology. I will establish whether there is a different prevalence between the general population and athletes and between males and females. I will also explore how the diagnostic criteria for cam and pincer morphology impact on estimates of prevalence.

Declarations

This work has been presented at national and international conferences:

Title: Prevalence of Cam Hip Shape Morphology; A Systematic Review Presenter: E Dickenson Event: International Society of Hip Arthroscopy Annual Scientific Meeting October 2014.

Title: Prevalence of Cam Hip Shape Morphology; A Systematic Review. Presenter: E Dickenson Event: British Hip Society Annual Congress March 2015.

This work has been published:

Dickenson E, Wall PDH, Robinson B, Fernandez M, Parsons H, Buchbinder R, Griffin DR. Prevalence of Cam Hip Shape Morphology; A Systematic Review. *Osteoarthritis and Cartilage*. 2016 24.6 949-961

2.1 Introduction

In Chapter 1, I described how the concept of FAI syndrome has been popularised following Ganz et al description in 2003.⁴ Since 2003 increasing numbers of patients are being diagnosed and treated for FAI syndrome.^{5,6,7,9} This may be a reflection of improvements in our understanding and awareness of the condition, a change in the prevalence of the condition, or other factors such as over diagnosis.⁸⁴ It seems unlikely that the prevalence of the disorder has suddenly changed in the last two decades.

It is proposed that cam morphology arises in response to hip loading in adolescence.⁸⁵⁻⁸⁷ Given that Western lifestyles have remained relatively consistent over this period (if anything there has been a reduction in physical activity) it seems unlikely the prevalence would have undergone a rapid increase.⁸⁸ It is more likely that an increase in awareness of FAI syndrome is responsible for the rise in diagnosis and treatment. However, we must consider the possibility that FAI syndrome is being over-diagnosed, especially given the emphasis on imaging findings when making the diagnosis.⁸⁹ Without knowing the normal appearances of hip imaging findings across a population or the diagnostic utility of positive imaging findings, the increase in treatment could be the result of over-diagnosis.⁸⁹

Despite the rise in the number of patients being diagnosed and treated, the evidence describing the natural history and epidemiology of the FAI has failed to keep up with the clinical popularisation. At present, it is unclear what the prevalence of cam or pincer morphology, or FAI syndrome, is in the general population. Furthermore, it is unclear what the natural history of the disorder is. Do all subjects with cam and pincer morphology develop FAI syndrome? It remains uncertain whether FAI syndrome is a self-limiting disorder, a disorder that left untreated results in chronic pain or whether it progresses to, or is an early presentation of OA.

Lumbar disc prolapse and subsequent back pain could offer a comparable natural history. There is an identifiable imaging finding (disc herniation), a proportion of these subjects may develop associated symptoms, the majority of cases are self

limiting, some patients require and benefit from surgery, while some develop chronic pain.⁹⁰⁻⁹² Could a similar natural history exist for FAI syndrome?

In order to understand the natural history of cam and pincer morphology and FAI syndrome it is necessary first to be able to describe the prevalence of cam and pincer morphology in the population. A number of studies have attempted to describe this using a variety of the methods. The estimates of prevalence reported in these studies is highly variable (ranging from 5 to 55%) while some studies suggest that cam morphology is more prevalent in certain athletic populations.^{85,93-99}

A systematic review of the available evidence was therefore conducted with the following objectives:

2.2 Objectives

1. To systematically review the available epidemiological evidence to describe the point prevalence of cam morphology.
2. To systematically review the available epidemiological evidence to describe the point prevalence of pincer morphology.

Secondary objectives were to:

1. Assess the relationship between hip shape and hip pain.
2. Establish the point prevalence of FAI syndrome.
3. Examine the influence that case definition has on prevalence estimates.
4. Examine the influence that different sub populations have on prevalence estimates.
5. Assess the probability of having bilateral cam or pincer morphology when one hip is affected.

2.3 Methods

I conducted a systematic review of the available literature in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)

guidance.¹⁰⁰ I registered a protocol for this review with PROSPERO international prospective register of systematic reviews registration number: CRD42013005135 (<http://www.crd.york.ac.uk/PROSPERO>).

2.3.1 Types of Studies

All studies that reported the prevalence of cam or pincer morphology or the prevalence of FAI syndrome secondary to cam or pincer impingement were considered for inclusion.

2.3.2 Types of Participants

Studies that included males and or females age 18 and over were considered for inclusion.

2.3.3 Types of Outcome Measures

Studies that defined cam or pincer morphology by previously published method were included (see Appendix Section 11.1). Different threshold values for certain methods, such as center edge angles (CEA) and alpha (α) angles is controversial. Different authors have used different thresholds.⁶¹ Therefore I did not choose a predetermined threshold to determine cam or pincer morphology. Studies were excluded if the prevalence was reported as a combination of estimates from different measures, without the data for each method being reported independently. For example the prevalence of cam morphology reported as a product of the prevalence of pistol grip deformity, an α angle greater than 55° and the presence of an osseous bump.

2.3.4 Search Method

Electronic Searches

A search for relevant articles was undertaken on the 24th October 2015 using AMED (Allied and Complementary Medicine Database) (1995- October 2015), MEDLINE (Medical Literature Analysis and Retrieval System Online) (1946- October 2015), EMBASE (Excerpta Medica Database) (1980- October 2015), CENTRAL (The

Cochrane Central Register of Control Trial The Cochrane Library 2014 Issue 10) and CINAHL (Cumulative Index to Nursing and Allied Health Literature Database)(1984-October 2015). The search strategy used for MEDLINE is displayed in Table 2, this was adapted for other databases.

Searching other resources

Identified papers were reference searched for potentially missed studies.

2.3.5 Selection of Studies

I reviewed records for eligibility by title, abstract and then as full text, in a three-stage determination method. This process was repeated independently by BR. Any disagreement between us was resolved by discussion with PW.

Table 2 MEDLINE Search Strategy

1	Femoroacetabular impingement.mp.	946
2	Femoro-acetabular impingement.mp.	70
3	Femoroacetabular-impingement.mp.	946
4	FAI.mp.	1105
5	Hip impingement.mp.	72
6	Cam-type.mp.	196
7	Pincer-type.mp.	95
8	Epidemiology/ or epidemiology.mp.	157869
9	Prevalence.mp.	462857
10	Incidence.mp.	607821
11	8 or 9 or 10	1124485
12	1 or 2 or 3 or 4 or 5 or 6 or 7	1790
13	11 and 12	221
14	Limit 13 to (English language and humans)	208

2.3.6 Data Extraction and Management

I extracted data onto predetermined forms. Data extracted included the number of participants, participant sex, participant age, population demographics (including if participants were athletes), imaging modality, diagnostic method, diagnostic criteria, prevalence data and the unit of analysis. Data reporting pain in relation to hip shape abnormality was recorded when available.

Unit of analysis issues- patients or hips

The preferred unit of analysis were studies that reported the prevalence of the hip shape in a population; that is, the number of individuals with either one or both hips

affected. This compared to other studies that reported only the number of hips affected, without fully accounting for all the hips in all the included subjects. This approach was taken because prevalence data in terms of subjects affected is more clinically relevant. Studies where the unit of analysis was hips were included and where possible the relationship between prevalence in hips and patients was explored.

2.3.7 Risk of Bias Assessment

I assessed the risk of bias using a tool specifically developed for prevalence studies.¹⁰¹ It includes ten criteria that assess the internal and external validity of the study. Each criterion is rated as high or low risk of bias and an overall judgment of bias risk is then rated as low, moderate or high. This tool has been found to demonstrate high inter-rater reliability.¹⁰¹

2.3.8 Assessment of Heterogeneity

I initially investigated the heterogeneity of the included studies by examination of the studies description. Studies were deemed clinically homogenous if they utilised the same imaging modality, the same diagnostic method and criteria, and reported the prevalence in terms of patients affected. In studies that were clinically homogenous I planned, with the help of a statistician, to investigate the percentage of variation between the studies due to heterogeneity using the I^2 statistic.¹⁰²

2.3.9 Data Synthesis

The overall prevalence was reported as a percentage of the unit of analysis i.e. patients or hips affected. Summary statistics were created, including means and 95% confidence intervals.

Where studies were clinically homogenous, I planned, with the help of a statistician, to conduct a meta-analysis using the inverse variance method with random effects.. The random effects model was chosen to allow for unspecified differences between studies.

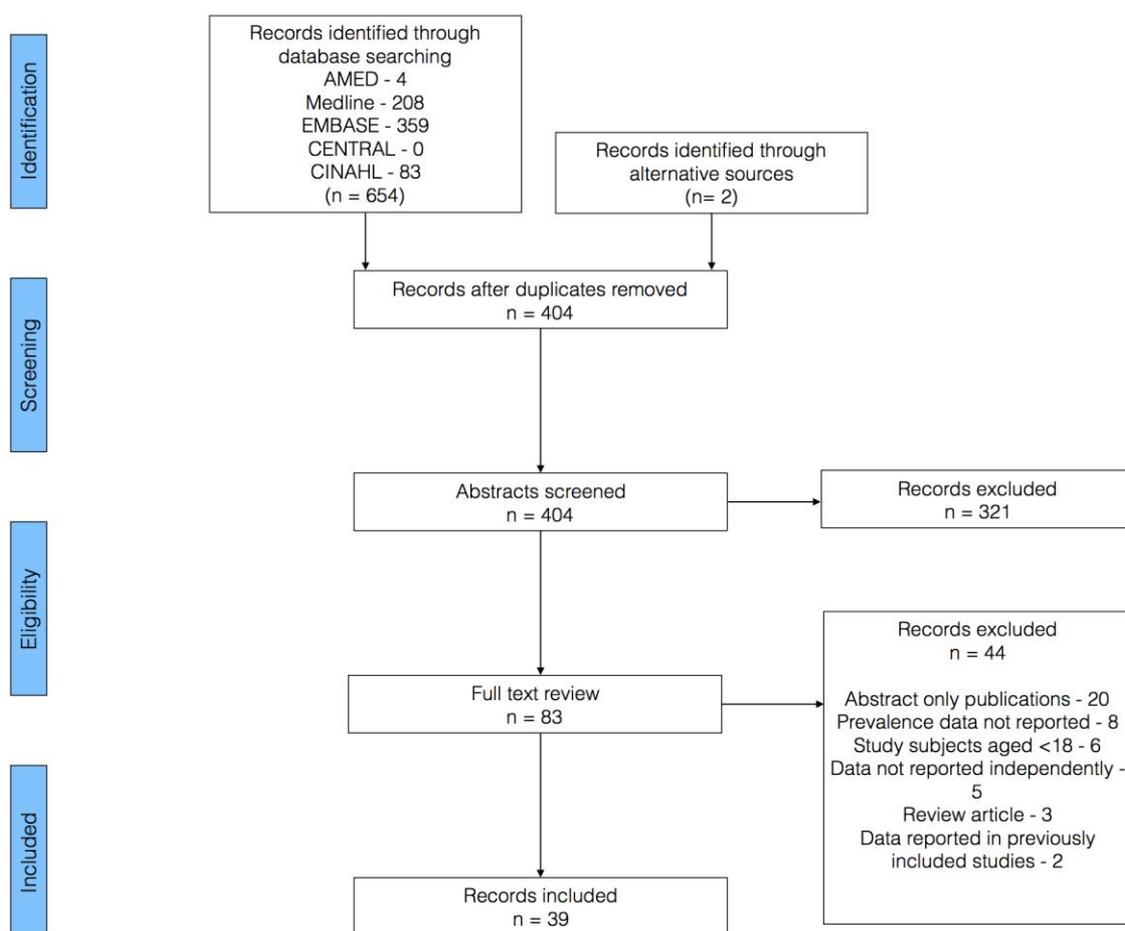
2.3.10 Subgroup analysis

If data was available a subgroup analysis was planned to determine if any difference in prevalence exists between professional athletes compared to the general population and between males and females.

2.4 Results

A PRISMA flow diagram of the search is displayed in Figure 8. The search returned 404 records after duplicates were removed. Following full text review of 83 records, 39 articles were included.

Figure 8 PRISMA Flow Diagram of Search Result



2.4.1 Excluded Studies

Of the 44 excluded studies, 20 were abstract only publications. In eight articles prevalence data for cam or pincer morphology was not reported, six studies

included study subjects who were less than 18 years old. In five articles, the prevalence data for each measure of morphology was not reported independently.

2.4.2 Included Studies

Table 6 provides a description of the included studies. Twenty-six studies assessed the prevalence of cam and pincer morphology, eleven assessed cam only and two studies assessed pincer morphology only. Twenty-six studies reported the prevalence of cam or pincer morphology as the number of hips affected; ranging from 48 to 4120 hips. Thirteen studies reported the numbers of subjects affected with the number of participants ranging from 44 to 3620.

2.4.3 Target Population

No study was truly general population based. In order to be general population based the included studies needed to represent the general population in factors such as gender, age, ethnicity and socio-economic background. Twenty-eight studies included males and females, four did not specify the sex of their subjects, four assessed only males and three assessed females only. Not all studies were explicit in stating whether participants were symptomatic. In twelve studies all subjects were symptomatic, nine studies contained a mix of symptomatic and asymptomatic subjects, seven studies contained asymptomatic individuals only and in eleven studies the presence of symptoms was not reported.

Six studies sampled non-representative subgroups of the general population. Hack et al included 200 hospital employees without hip pain whom they invited to undergo hip MR scans.⁹⁴ Agricola et al included 1411 participants in the Cohort Hip and Cohort Knee (CHECK) study who were identified as having hip or knee pain.¹⁰³ Gosvig et al included a subset of subjects from the Copenhagen Osteoarthritis Study (COS).⁹⁸ The COS was formed as a sub-study of the Copenhagen City Heart Study III in which participants completed a general musculoskeletal questionnaire.¹⁰⁴ Participants were included in the COS if they had a positive response to $\geq 4/50$ musculoskeletal questions (2939 participants). Additionally the COS included age and sex matched participants who had positive answers to $\leq 3/50$ musculoskeletal questions (1202 participants).¹⁰⁴ Gosvig et al assessed 3202 subjects from the COS.

They excluded 949 participants due to: unreadable or poorly centred radiographs (N=181), presence of childhood hip disorder (N=57), rheumatoid arthritis (N=141), and arthrosis (N=502).⁹⁸ Laborie et al included 2060 subjects from Norway under long term follow up after a randomised controlled trial of new-borns comparing ultrasound screening with clinical assessment for developmental dysplasia of the hip. The study subjects were aged 17-20 years.¹⁰⁵ Leunig et al assessed 80 female hips, aged 20, sampled from local Swiss schools. Subjects were selected for hip MRI based on stratification by hip internal rotation.¹⁰⁶ Reichenbach et al examined 244 male hips, aged 20, who were sampled from Swiss army recruits. Subjects were also selected for hip MRI based on stratification by hip internal rotation.¹⁰⁷

In twenty-four studies the target population was a subgroup of a clinical population some of whom had hip pain. Four studies assessed participants with hip pain undergoing arthroplasty (N= 62, 258, 142, 946 hips respectively).^{93,108-110} Two studies assessed hips that had sustained femoral neck stress fractures but the presence of preceding hip pain was not reported (n=53 participants and n=27 hips respectively).^{99,111} Two studies included patients undergoing imaging for “non hip-related pathology” and the presence/absence of hip pain in these subjects was not determined (n= 994 and 755 hips respectively).^{112,113} Two studies (n=202 and n=68 hips) assessed subjects referred groin pain and adductor related pain respectively.^{114,115} One study compared 3 groups of patients; one group of patients undergoing surgical hip dislocation (n=96 hips), one undergoing peri-acetabular osteotomy (n= 74hips) and a group of asymptotic footballers (n= 134).¹¹⁶ One study included hips (n=522) that had undergone a radiograph but excluded cases with a suspicion of FAI, OA, DDH, fracture, tumours following a THR.¹¹⁷ One study assessed 100 hips in subjects undergoing a peri-acetabular osteotomy while another inspected the contralateral hips in subjects undergoing PAO (n=87).^{118,119} One study included female hips (n=398) within the Beijing OA study and the USA study of osteoporosis.¹²⁰ Two studies recruited asymptomatic subjects from a hospital outpatient clinic (n=184 participants and 164 hips).^{121,122} Seven studies included participants who had undergone a CT scan for another indication.¹²³⁻¹²⁹ Tsitskaris et al included 45 participants who underwent CT scan for suspected intra-abdominal pathology; hip symptoms were measured with the non-arthritic hip score (NAHS).¹²³ Kang et al included 50 participants who had undergone a CT scan

following major trauma; the presence of pain was not assessed.¹²⁴ Five studies included subjects without hip/ groin pain having a CT scan for any “non orthopaedic” indication (n=77, 131, 201 participants and n=103, 473 hips).¹²⁵⁻¹²⁹

In the manuscripts that assessed athletes, the types of sport differed between studies. Johnson et al included 50 former high-level youth soccer players and 50 controls and excluded subjects who had sought treatment for groin/hip pathology.⁹⁶ Lahner et al assessed semi-professional soccer players (n=22) compared to recreational players from a university (n=22).¹³⁰ Gerhardt et al reviewed pelvic radiographs of 95 footballers taken during routine pre-season screening at 4 clubs; the presence of symptoms wasn't recorded.¹³¹ Tak et al assessed 63 professional soccer players from 2 clubs, the presence of hip symptoms was not reported.¹³² Kolo et al included 30 professional female ballet dancers and assessed 59 of their hips (mix of symptomatic and asymptomatic), compared to 28 hips from 14 age-matched asymptomatic non-dancing female controls.³³ Mariconda et al included 24 Capoeira competitors from a single club and assessed 48 of their hips, excluding people with hip disorders.¹³³ Nepple et al and Larson et al assessed male American football players who had had clinically indicated radiographs performed. Larson et al included 125 participants and assessed 239 hips, of which 75 were symptomatic (hip/groin pain).⁹⁷ Nepple et al assessed 123 hip radiographs performed in an unknown number of participants for pain or injury but excluded those attributed to intra-articular pathology.⁸² Lahner et al assessed 22 top ranking track and field athletes and 22 controls not participating in athletics, the presence of hip symptoms was reported using the hip outcome score.¹³⁴

2.4.4 Measures of cam morphology

Numerous different methods were used for determining the presence of cam morphology; see Table 3. α angles were the most frequently utilised measure, however 16 different imaging modalities and or imaging planes were used with seven different threshold values (some studies used more than 1 imaging planes and or threshold values). The threshold values for α angles ranged from 50 to 83°, 55° was the most frequently used value (n=16). Some studies used different thresholds values for males and females.^{98,110,112,113}

2.4.5 Measures of pincer morphology

Eleven different methods were used to determine the presence of pincer morphology; see Table 4. Cross over sign and center edge angle (CEA) were the most frequently used measures (n=20 and n=17 respectively). In the case of CEA three different threshold values were used from 39 to 45°.

Table 3 Measures of Cam morphology

Measure	Frequency
Alpha angle	26
Pistol grip deformity	4
Head neck offset	3
Neck shaft angle	3
Head neck offset grade	2
Head neck offset ratio	2
Focal prominence/ abnormal head neck junction	2
Triangular index	2
Impingement angle	1
Head ratio	1

Table 4 Measures of Pincer Morphology

Measure	Frequency
Cross over sign	20
Centre edge angle	17
Tonnis angle	9
Coxa profunda	7
Acetabular anteversion	6
Ischial spine sign	5
Posterior wall sign	4
Protrusio acetabuli	3
Acetabular depth	2
Sharps angle	1
Anterior acetabular head index	1

2.4.6 Risk of Bias

Table 5 provides the full details of the risk of bias assessment.

Thirty-eight studies were judged to be at high potential risk of bias, most commonly because of lack of external validity as the sampling frame was not representative of the general population or the nominated target population. Other issues included use of hips rather than participants as the denominator for prevalence estimates and inclusion of participants with only painful or pain free hips. Laborie et al was rated a moderate risk of bias, the target population was not representative of the

general population (targeted 17-20 year olds only) and there was a 48% non-response.¹⁰⁵

Table 5: Included studies Risk of Bias

Study	Risk of Bias 1	Risk of Bias 2	Risk of Bias 3	Risk of Bias 4	Risk of Bias 5	Risk of Bias 6	Risk of Bias 7	Risk of Bias 8	Risk of Bias 9	Risk of Bias 10	Risk of Bias 11
Agricola 2012 ¹⁰³	High	Low	High	High	Low	Low	Low	Low	Low	High	High
Anderson 2012 ¹¹⁶	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Bowler 2011 ¹¹⁰	High	High	High	Low	Low	High	Low	Low	Low	High	High
Carey 2012 ⁹⁹	High	High	High	Low	Low	Low	Low	Low	Low	High	High
De Bruin 2013 ¹¹⁷	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Diesel 2015 ¹²¹	High	High	High	Low	High						
Dudda 2011 ¹²⁰	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Ergen 2014 ¹²⁷	High	High	High	High	Low	Low	Low	Low	Low	Low	High
Fukushima 2014 ¹¹⁹	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Gerhardt 2012 ¹³¹	High	High	High	Low	High						
Gosvig 2010 ¹³⁵	High	Low	High	Low	Low	High	Low	Low	Low	Low	High
Goldin 2015 ¹¹¹	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Hack 2010 ⁹⁴	High	High	High	High	Low	Low	Low	Low	Low	Low	High
Hashimoto 2014 ¹⁰⁸	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Ida 2014 ¹¹⁸	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Johnson 2012 ⁹⁶	High	High	High	Low	High						
Joo 2013 ¹¹²	High	High	High	Low	Low	High	Low	Low	Low	High	High
Jung 2011 ¹¹³	High	High	High	Low	Low	High	Low	Low	Low	High	High
Kang 2010 ¹²⁴	High	High	High	Low	High						
Kim 2015 ¹²⁹	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Kolo 2013 ³³	High	High	High	High	Low	Low	Low	Low	Low	High	High
La France 2014 ¹⁰⁹	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Laborie 2011 ¹⁰⁵	High	Low	Low	High	Low	Low	Low	Low	Low	Low	Moderate
Lahner 2014 ¹³⁰	High	High	High	High	Low	Low	Low	Low	Low	Low	High
Lahner 2014 ¹³⁴	High	High	High	High	Low	Low	Low	Low	Low	Low	High

Larson 2013 ⁹⁷	High	High	High	High	Low	Low	Low	Low	Low	Low	High
Leunig 2013 ¹⁰⁶	High	Low	High	High	Low	Low	Low	Low	Low	High	High
Mariconda 2014 ¹³³	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Mimura 2015 ¹²⁶	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Mori 2014 ¹¹⁴	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Nepple 2012 ⁸²	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Omoumi 2014 ¹²⁵	High	High	High	Low	Low	Low	Low	Low	Low	Low	High
Reichenbach 2010 ¹⁰⁷	High	Low	High	High	Low	Low	Low	Low	Low	High	High
Scheidt 2015 ¹²²	High	High	High	High	Low	Low	Low	Low	Low	High	High
Tak 2015 ¹³²	High	High	High	Low	Low	Low	Low	Low	Low	Low	High
Takeyama 2009 ⁹³	High	High	High	Low	Low	Low	Low	Low	Low	High	High
Tsitskaris 2012 ¹²³	High	High	High	Low	Low	Low	Low	Low	Low	Low	High
Van Houcke 2015 ¹²⁸	High	High	High	Low	Low	Low	Low	Low	Low	Low	High
Weir 2011 ¹¹⁵	High	High	High	Low	Low	Low	Low	Low	Low	High	High

Items included on the risk of bias tool:

Risk of Bias 1: Was the study's target population a close representation of the national population in relation to relevant variables, e.g., age, sex, occupation?

Risk of Bias 2: Was the sampling frame a true or close representation of the target population?

Risk of Bias 3: Was some form of random selection used to select the sample, OR, was a census undertaken?

Risk of Bias 4: Was the likelihood of non-response bias minimal?

Risk of Bias 5: Were data collected directly from the subjects (as opposed to a proxy)?

Risk of Bias 6: Was an acceptable case definition used in the study?

Risk of Bias 7: Had the study instrument that measured the parameter of interest (e.g., prevalence of LBP) been tested for reliability and validity (if necessary)?

Risk of Bias 8: Was the same mode of data collection used for all subjects?

Risk of Bias 9: Was the length of the shortest prevalence period for the parameter of interest appropriate?

Risk of Bias 10: Were the numerator(s) and denominator(s) for the parameter of interest appropriate?

Risk of Bias 11: Summary item on the overall risk of study bias.

2.4.7 Prevalence estimates cam morphology

As no studies included the same target population or measured cam hip shape using the same methods, data could not be pooled or displayed in graphical form.

There was a wide range of prevalence estimates across studies reflecting different study populations (including subjects with and without pain), the different diagnostic measures, diagnostic criteria and imaging modalities. Hack et al estimated prevalence of cam morphology in asymptomatic hospital workers to be between 14 and 53% depending on which case definition was used (α angle threshold of 50.5° at 3 o'clock and 50.5° at 1:30 o'clock respectively).⁹⁴ From a subset of the COS, Gosvig et al estimated the prevalence of cam morphology to be

12% in males and 5% in females using different diagnostic criteria for each sex (α angle cut off value of 83° for males and 57° for females).⁹⁸ Although they did not present the data, Gosvig et al reported that there was no correlation between hip pain and cam morphology.⁹⁸ Agricola et al reported that cam morphology was present in 11% of hips among participants with hip or knee pain in the CHECK cohort.¹⁰³ Laborie et al estimated the prevalence of cam morphology to be 6% when assessing for a focal prominence and 11% of participants when assessing for a pistol grip deformity on AP and frog lateral radiographs.¹⁰⁵

The prevalence estimates of cam morphology in studies that included a clinical population ranged from 9 to 61% of participants and 0 to 68% of hip joints,^{110,119,121,125} while in studies that included different groups of athletes the prevalence ranged from 48 to 75% of participants and 2 to 92% of hip joints.^{33,82,96,97}

Seven studies reported prevalence by both the number of participants and the number of hips affected, accounting for all the hips in all the participants.^{121,123,124,128,130,132,134} Based on these seven studies the probability of having bilateral cam morphology, when one hip was affected, is 0.47 (95% CI: 0.35 to 0.59).

Five studies reported prevalence for males and female participants separately with each study using the same case definitions for both genders.^{94,96,105,123,131} All studies found that cam morphology was more prevalent in males than females (males 29, 25, 58, 27 and 22% versus females 20, 5, 34, 10 and 3% respectively).^{94,96,105,123,131}

Four studies included a mixture of participants with and without hip pain and reported the results of cam morphology for each group.^{97,98,123,133} Gosvig et al reported that there was no statistically significant difference in the prevalence of hip shape abnormalities between those with and without hip pain.^{97,98} Tsitskaris et al found no correlation between the NAHS and the presence of cam.¹²³ However Mariconda et al found a statistically significant correlation between cam morphology (α angles $>60^\circ$) and hip pain, while Larson et al found a statistically significant association between increasing α angle and hip/ groin pain.^{97,133}

2.4.8 Prevalence estimates pincer morphology

There was a large discrepancy in prevalence estimates for pincer morphology. Due to the high degree of study heterogeneity, I was unable to pool this study data or display it in graphical form.

Gosvig et al estimated the prevalence of pincer morphology to be 18% of participants in the COS.¹³⁵ Laborie et al used three different measures of pincer morphology; cross over sign, posterior wall sign and excessive acetabular depth and found the prevalence to be 48, 16 and 9% respectively.¹⁰⁵

Of the studies that assessed various clinical populations prevalence estimates ranged 5 to 40% of participants, using a Tonnis angle of less than 0° and a cross over sign respectively, and 0.4 to 84% of hips, using the presence of acetabular protrusion and cross over sign respectively.^{117,120,125} Three studies of different athletic populations assessed for pincer morphology the prevalence of participants affected ranged from 0 to 71% when using a CEA greater than 40° and a cross over sign respectively.^{97,134}

Three studies (Gosvig et al, Laborie et al and Gerhardt et al) compared the prevalence of pincer morphology in male and female participants; there was no overall pattern for a higher prevalence of pincer in either sex.^{105,131,135} Three studies (Gosvig et al, Mariconda et al and Larson et al) reported the relationship between pain and pincer morphology, they were unable to demonstrate an association.^{97,133,135}

Table 6 Description and demographics of included studies

Study author	Study summary	Unit of analysis	Number of participants (number male, female)	Number of hips (Number male, female)	Subjects mean age (Range)	Presence of hip pain/ symptoms	Diagnostic criteria			No. of hips affected	No. of participants affected	Prevalence % hips affected (males, female)	Prevalence % participants affected (males, females)
							Imaging modality	Diagnostic measure	Criterion for diagnosis				
Agricola 2012 ¹⁰³ Netherlands	Subset of general population; Study of radiographs of subjects in the "cohort hip and cohort knee" (CHECK) with early OA of the knee or hip.	Hips	NR	1411 (282, 1129)	56 (45-65)	All participants had hip and or knee pain	AP radiograph	Cam; Alpha angle	> 60°	156	NR	11 (NR)	NR
Gosvig 2010 ¹³⁵ Denmark	Subset of general population. Subset of participants from Copenhagen Osteoarthritis a Sub study of the Copenhagen City Heart Study	Participants	3620 (1332, 2288)	NR	60 (20-90)	Mixture of participants with and without pain. Numbers NR.	AP radiograph	Cam; Triangular index	> 0mm	NR	379	NR	11 (20, 5)
								Pincer; centre edge angle	> 45°	NR	646	NR	18 (15, 19)
Hack 2010 ⁹⁴ Canada	Subset of general population; Asymptomatic volunteers, who were hospital workers, with no prior hip complaints.	Participants	200 (89, 111)	NR	29 (21-51)	All participants asymptomatic	MRI, 1:30 o'clock	Cam; Alpha angle	> 55°	NR	67	NR	34 (52,19)
							MRI, 1:30 o'clock		> 50.5°	NR	106	NR	53 (75, 35)
							MRI, 3 o'clock		> 50.5°	NR	28	NR	14 (25, 5)
Laborie 2011 ¹⁰⁵ Norway	General population; Participants recruited from long term follow up of a randomised trial of all new-borns assessing rates of hip dysplasia (treatment arms; general, selective or ultrasound screening)	Participants and hips	2060 (868, 1192)	4120 (1736, 2384)	19 (17-20.)	NR	AP and frog lateral radiograph	Cam; pistol grip deformity	Presence of pistol grip deformity	NR	226	NR	11 (22, 3)
								Cam; focal prominence	Presence of focal prominence	NR	120	NR	6 (10, 3)
							AP radiograph	Pincer; excessive acetabular depth	An extension of the acetabular rim in an inferior or lateral direction	NR	185	NR	9 (15, 5)
								Pincer; cross over sign	Presence of cross over sign	NR	988	NR	48 (51, 46)
								Pincer; posterior wall sign	Presence of posterior wall sign	NR	334	NR	16 (23, 11)

Leunig 2013 ¹⁰⁶ Switzerland	Subset of general population. Study of females aged 18-19 attending local schools. Subjects selected for MRI randomly stratified by degree of hip internal rotation. Only 1 hip in each participant imaged	Hips	NR	80 (0, 80)	20 (NR)	Subjects with pain of greater than 3/5 on likert scale were excluded.	MRI around axis of neck	Cam; head neck offset grade	Grade 2-3	0	NR	0 (NA)	NR
							MRI; axial oblique in line with centre of femoral head	Pincer; acetabular depth	< 3mm	25	NR	31 (NA)	NR
Reichenbach 2010 ¹⁰⁷ Switzerland	Subset of general population. Swiss men attending army recruitment centre Between March and July 2005, underwent examination. Subjects selected for MRI randomly stratified by degree of hip internal rotation.	Hips	NR	244 (244, 0)	20 (NR)	Subjects with pain of greater than 3/5 on likert scale were excluded.	MRI around axis of neck	Cam; head neck offset grade	Grade 2-3	67	NR	28 (NA)	NR
Anderson 2012 ¹¹⁶ USA	Clinical population. Study made of combining of 3 groups: a group of asymptomatic male footballers, a group of patients undergoing surgical hip dislocation and a group of patients who had undergone a PAO	Hips	NR	304 (NR) Group 1 footballers: 134 Group 2 PAO: 74 Group 3 SHD: 96	25 (15-51)	Group 1 (footballers) 62/67 players asymptomatic. Group 2 and group 3 symptomatic	AP radiograph	Pincer; coxa profunda	Presence of coxa profunda	Group 1: 45 Group 2: 43 Group 3: 54	NR	Group 1: 34 (NR) Group 2: 58 (NR) Group 3: 56 (NR)	NR
								Pincer; centre edge angle	> 40°	Group 1: 8 Group 2: 0 Group 3: 21	NR	Group 1: 6 (NR) Group 2: 0 (NR) Group 3: 22 (NR)	NR
								Pincer; tonnis angle	< 0°	Group 1: 19 Group 2: 0 Group 3: 8	NR	Group 1: 14 (NR) Group 2: 0 (NR) Group 3: 8 (NR)	NR
								Pincer; cross over sign	Presence of cross over sign	Group 1: 92 Group 2: 21 Group 3: 29	NR	Group 1: 69 (NR) Group 2: 28 (NR) Group 3: 30 (NR)	NR

								Pincer; posterior wall sign	Presence of posterior wall sign	Group 1: 97 Group 2: 61 Group 3: 41	NR	Group 1: 72 (NR) Group 2: 82 (NR) Group 3: 43 (NR)	NR
Bowler 2011 ¹¹⁰ USA	Clinical population; Review of radiographs of adults <50years undergoing arthroplasty	Hips	142 (92, 50)	NR	44 (20-49)	All hips symptomatic	AP Radiograph	Cam; alpha angle	Males > 69°	63	NR	68	NR
									Females > 51°	29	NR	58	NR
								Pincer; cross over sign	Presence of cross over sign	16	NR	11 (NR)	NR
Carey 2012 ⁹⁹ USA	Clinical population; soldiers who had sustained femoral neck stress fractures	Hips	53 (24, 29)	NR	NR	Hip pain prior to injury NR	Frog lateral radiographs	Cam; alpha angle	> 50°	29	NR	55 (NR)	NR
							AP radiograph	Pincer; cross over sign	Presence of cross over sign	27	NR	50 (NR)	NR
								Pincer; centre edge angle	> 40°	25	NR	47 (NR)	NR
De Bruin 2013 ¹¹⁷ Netherlands	Clinical population. Review of subjects in one institution who underwent pelvic x-rays between 2008-09 aged 20-60 excluding cases where there was suspicion of FAI, OA, DDH, fractures, tumours and THR	Hips	NR	522 (200, 322)	NR (20-59)	72/ 262 patients had hip/ groin pain.	AP radiograph	Pincer; coxa profunda	Presence of coxa profunda	339	NR	65 (42, 79)	NR
								Pincer; acetabular protrusion	Presence of acetabular protrusion	2	NR	0.4 (0.5, 0.3)	NR
								Pincer; Centre edge angle	> 40°	101	NR	19 (23, 17)	NR
								Pincer; Tonnis angle	< 0°	160	NR	31 (36, 28)	NR
								Pincer; cross over sign	Presence of cross over sign	80	NR	15 (18, 14)	NR
								Cam; pistol grip deformity	Presence of pistol grip deformity	68	NR	13 (26, 5)	NR
								Cam; neck shaft angle	< 125°	61	NR	11 (17, 8)	NR
Diesel 2015 ¹²¹ Brazil	Clinical population: non athletic subjects attending medical screening appointments aged 20-60 years	Participants and hips	184 (91,93)	368 (182, 186)	34 (20-60)	All participants asymptomatic	Dunn lateral radiograph	Cam; alpha angle	> 55°	50	35	14 (NR)	19 (NR)
							AP radiograph	Cam; triangular index	Abnormal triangular index	25	16	7 (NR)	9 (NR)
								Pincer; centre edge angle	> 40°	NR	23	NR	12 (NR)
								Pincer; tonnis angle	< 0°	NR	51	NR	28 (NR)
								Pincer; cross over sign	Presence of cross over sign	NR	34	NR	19 (NR)

Dudda 2011 ¹²⁰ China and USA	Clinical population. Females from Beijing OA Study and USA Study of Osteoporotic fractures aged over 60 and 65 respectively with no radiographic signs of OA	Hips	NR	398 (0, 398)	71 (NR)	NR	AP radiograph	Pincer; centre edge angle	> 40°	26	NR	7 (NA)	NR	
								Pincer; Tonniss angle	< 0°	32	NR	8 (NA)	NR	
								Pincer; cross over sign	Presence of cross over sign	334	NR	84 (NA)	NR	
								Cam; impingement angle	< 70°	31	NR	8 (NA)	NR	
								Cam; head ratio	> 1.35	14	NR	4 (NA)	NR	
Ergen 2014 ¹²⁷ Turkey	Clinical population; adults aged 18-40 undergoing CT pelvis for non hip pathology	Hips	68 (38, 30) [5 hips in 5 subjects excluded due to positive impingement tests]	131 (NR)	33 (19-46)	All participants asymptomatic	CT; 12-3 o'clock	Cam; alpha angle	> 55°	31	NR	24 (NR)	NR	
							CT; axial oblique	Cam, femoral head neck offset	< 8mm	37	NR	27 (NR)	NR	
							CT; coronal transparent 3D reconstruction	Pincer; centre edge angle	> 40°	33	NR	26 (NR)	NR	
							CT; axial slice	Pincer; acetabular anteversion	< 15°	15	NR	12 (NR)	NR	
Goldin 2015 ¹¹¹ USA	Clinical population; subjects aged 18-40 years who had sustained femoral neck stress fractures	Hips	NR	24 (3,21) 6 AP radiographs had inadequate rotation.	27 (19-39)	Hip pain prior to injury NR	Cross table lateral radiographs	Cam; alpha angle	> 50°	4	NR	17 (33, 14)	NR	
								Cam; anterior head neck offset ratio	< 0.18	7	NR	29 (NR)	NR	
								Cam; abnormal head neck junction	Presence of abnormal head neck junction	6	NR	25	NR	
								AP radiographs	Pincer; coxa profunda	Presence of coxa profunda	14/18	NR	78	NR
									Pincer; Cross over sign	Presence of cross over sign	6/18	NR	33	NR
									Pincer; centre edge angle	> 40°	1 / 24	NR	4	NR
Ida 2014 ¹¹⁸ Japan	Clinical population; adults who had undergone a periacetabular osteotomy for acetabular dysplasia between 2009 and 2012.	Hips	NR	100 (8,92)	38 (14-60)	All hips symptomatic	Cross table lateral radiographs	Cam; alpha angle	> 55°	40	NR	40 (63, 38)	NR	
	Clinical population; subjects over 20 years	Hips	NR	103 (57, 46)	59 (NR)	NR	CT; 12-3 o'clock	Cam; alpha angle	> 50°	53	NR	52 (NR)	NR	

Mimura 2015 ¹²⁶ Japan	undergoing CT pelvis for "non orthopaedic" indications						CT; axial slices	Pincer; acetabular anteversion	Any negative value	17	NR	17 (NR)	NR
Scheidt 2015 ¹²² Brazil	Clinical population; consecutive volunteer subjects aged 40-60 attending outpatients in 1 institution	Hips	82	164 (56, 108)	50 (40-60)	All asymptomatic hips	Dunn lateral radiograph	Cam; alpha angle	> 50°	41	NR	25 (34,11)	NR
							AP radiograph	Pincer; cross over sign	Presence of cross over sign	20	NR	13 (NR)	NR
								Pincer; posterior wall sign	Presence of posterior wall sign	58	NR	37 (NR)	NR
								Pincer; Ischial spine sign	Presence of ischial spine sign	47	NR	30 (NR)	NR
Van Houcke 2015 ¹²⁸ Belgium and Hong Kong	Clinical population: subjects undergoing pelvic CT for abdominal pain or trauma in 1 institution in Belgium and 1 institution in Hong Kong	Participants and Hip	Belgium: 99 (58, 41) Hong Kong: 102 (47,55)	Belgium: 198 (116, 82) Hong Kong: 204 (94, 110)	NR (18-40)	All asymptomatic hips	CT: 1:30 o'clock	Cam; alpha angles	> 55°	Belgium: 66. Hong Kong: 37	NR	Belgium: 33 (29, 39). Hong Kong: 19 (23, 14)	NR
							CT; coronal slab	Cam; neck shaft angle	< 125°	Belgium: 32. Hong Kong: 26	NR	Belgium: 16 (24, 5). Hong Kong: 13 (16, 10))	NR
							CT; axial oblique	Cam; anterior offset ratio	< 0.13	Belgium: 6. Hong Kong: 3	NR	Belgium: 3 (3, 2). Hong Kong: 2 (1, 2)	NR
							CT; axial slice	Pincer; acetabular anteversion	< 15°	Belgium: 27. Hong Kong: 45	NR	Belgium: 14 (14, 13). Hong Kong: 22 (34, 12)	NR
							CT; transparent coronal reconstruction	Pincer; cross over sign	Presence of cross over sign	Belgium: 57. Hong Kong: 14	NR	Belgium: 29 (35, 20). Hong Kong: 7 (13, 2)	NR
							CT; transparent coronal reconstruction	Pincer; ischial spine sign	Presence of ischial spine sign	Belgium: 41. Hong Kong: 39	NR	Belgium: 21 (25, 15). Hong Kong: 19 (35, 6)	NR
							CT; transparent coronal reconstruction	Pincer; centre edge angle	> 45°	Belgium: 32. Hong Kong: 18	NR	Belgium: 16 (16, 16). Hong Kong: 9 (16, 3)	NR

							CT; transparent coronal reconstruction	Pincer; sharps angle	< 33°	Belgium: 23. Hong Kong: 6	NR	Belgium: 12 (14, 9). Hong Kong: 3 (4, 2)	NR
							CT; transparent coronal reconstruction	Pincer; tonnis angle	< 5°	Belgium: 2. Hong Kong: 8	NR	Belgium: 1 (2, 0). Hong Kong: 4 (7, 1)	NR
							CT; transparent coronal reconstruction	Pincer; anterior acetabular head index	> 0.9	Belgium: 66. Hong Kong: 103	NR	Belgium: 33 (33, 34). Hong Kong: 50 (55, 46)	NR
Kim 2015 ¹²⁹ South Korea	Clinical population: subjects who had undergone a CT pelvis only hips with no clinical or radiological (e.g. OA, dysplasia or fractures) abnormality assessed.	Hips	NR	473 (292, 181)	NR	All hips asymptomatic	CT; 3 o'clock	Cam; alpha angle	> 55°	85	NR	18 (20,14)	NR
								Cam; head neck offset	< 8mm	48	NR	33 (11, 15)	NR
							CT axial slice at deepest point of acetabulum	Pincer; acetabular version	< 15°	131	NR	28 (31, 22)	NR
							CT, coronal maximal intensity projection	Pincer; centre edge angle	> 40°	126	NR	27 (28, 24)	NR
Fukushima 2014 ¹¹⁹ Japan	Clinical population. Assessment of contralateral hip in patients who underwent surgery for dysplasia. Excluding patients with other known hip pathology.	Hips	NR	87 (7, 80)	44 (20-56)	NR	AP radiograph	Pincer; cross over sign	Presence of cross over sign	24	NR	28 (NR)	NR
								Cam; pistol grip deformity	Presence of pistol grip deformity	0	NR	0 (NR)	NR
Hashimoto 2014 ¹⁰⁸ Japan	Clinical population. Patients undergoing total hip replacement in 2 centres in Japan; sub study of those with unknown aetiology for OA.	Hips	NR	62 (NR)	71 (NR)	All hips symptomatic	Cross table lateral radiograph	Cam; alpha angle	> 50°	17	NR	27 (NR)	NR
							AP radiograph	Pincer; coxa profunda	Presence of coxa profunda	23	NR	37 (NR)	NR
								Pincer; cross over sign	Presence of cross over sign	15	NR	24 (NR)	NR
Jung 2011 ¹¹³ USA	Clinical population; participants who had undergone CT performed for non-hip pathology.	Hips	NR	755 (215, 540)	60 (26-93)	NR	CT scout (12 o'clock)	Cam; alpha angle	Male > 83°	30	NR	14	NR
									Females > 57°	30	NR	6	NR
Joo 2013 ¹¹² South Korea	Clinical population; Asymptomatic Asian adults who underwent MRI spine for back pain	Hips	NR	994 (622, 372)	53 (18-96)	NR	MRI scout, 12 o'clock	Cam; alpha angle	Males > 83°	2	NR	0.5	NR
									Females > 57°	19	NR	3	NR

Kang 2010 ¹²⁴	Clinical population; adults who had CT scan for trauma or abdominal pain	Participants and hips	50 (23, 27)	100 (46, 54)	NR (15-40)	NR	CT, 3 o'clock	Cam; alpha angle	> 55°	10	6	10 (11, 9)	12 (NR)
								Cam; head neck offset	< 8mm	12	6	12 (9, 15)	12 (9, 15)
							CT, assessed on AP transparent maximum intensity projection	Pincer; centre edge angle	> 40°	16	9	16 (20, 13)	18 (NR)
							CT; assessed transparent on AP maximum intensity projection	Pincer; cross over sign	Presence of cross over sign	20	NR	20 (NR)	NR
La France 2014 ¹⁰⁹ USA	Clinical population; participants undergoing hip resurfacing or arthroplasty by 1 surgeon. Excluding participant s with Perthes, SUFE, dysplasia, inflammatory arthroplasty or posttraumatic arthritis.	Hips	255 (NR)	NR	59 (36-86)	All hips symptomatic	Cross table lateral radiograph	Cam; alpha angle	> 55°	162	NR	64 (NR)	NR
								AP radiograph	Pincer; coxa profunda	Presence of coxa profunda	78	NR	31 (NR)
							Pincer; acetabular protrusio		Presence of acetabular protrusio	3	NR	1 (NR)	NR
							Pincer; cross over sign		Presence of cross over sign	40	NR	16 (NR)	NR
Pincer; ischial spine sign	Presence of ischial spine sign	51	NR	20 (NR)	NR								
Mori 2014 ¹¹⁴ Japan	Clinical population; participants with groin pain and tonnis grade <2	Hips	NR	202 (65, 137)	52 (11-83)	All participants had groin pain	Frog lateral radiograph	Cam; alpha angle	> 50°	29	NR	14 (NR)	NR
							AP radiograph	Pincer; cross over sign	Presence of cross over sign	10	NR	5 (NR)	NR
								Pincer; centre edge angle	> 40°	9	NR	5 (NR)	NR
Omoumi 2014 ¹²⁵ Belgium	Clinical population; asymptomatic patients undergoing CT for non-hip related pathology	Participants	77 (41, 36)	NR	49 (NR)	All hips asymptomatic	CT, 1;30 o'clock	Cam; alpha angle	> 55°	NR	47	NR	61 (NR)
							CT, 1;30 o'clock		> 60°	NR	36	NR	47 (NR)
							CT, 3 o'clock		> 55°	NR	23	NR	30 (NR)
							CT, 3 o'clock		> 60°	NR	13	NR	17 (NR)
							CT, thick coronal slab	Pincer; centre edge angle	> 40°	NR	12	NR	16 (NR)
								Pincer; tonnis angle	< 0°	NR	4	NR	5 (NR)
Pincer; cross over sign	Presence of cross over sign	NR	31	NR	40 (NR)								

								Pincer; posterior wall sign	Presence of posterior wall sign	NR	20	NR	26 (NR)
							CT; axial plane	Pincer; acetabular retroversion	< 15°	NR	17	NR	22 (NR)
Takeyama 2009 ⁹³ Japan	Clinical population; participants admitted for primary surgery of the hip	Hips	NR	946 (NR)	54 (12-92)	All hips were symptomatic	AP radiograph	Cam; alpha angle	> 60°	3	NR	0.3 (NR)	NR
Tsitskaris 2012 ¹²³ UK	Clinical population; participants undergoing CT for trauma or abdominal pain	Participants and hips	45 (21, 24)	90 (42, 48)	33 (20-40)	Presence of hip pain NR. Mean values for non-arthritic hip scores reported in 34/45 participants.	CT, 12 o'clock	Cam; alpha angle	> 55°	17	11	19 (21,17)	24 (29,21)
Weir 2011 ¹¹⁵ Netherlands	Clinical population. Patients presenting to 1 hospital with longstanding adductor related groin pain	Hips	NR	68 (NR)	30 (18-45)	All participants had groin had	AP radiograph	Cam; pistol grip deformity	Presence of pistol grip deformity	27	NR	40 (NR)	NR
								Cam; neck shaft angle	< 125°	2	NR	3 (NR)	NR
								Pincer; coxa profunda	Presence of coxa profunda	23	NR	34 (NR)	NR
								Pincer centre edge angle	> 39°	20	NR	29 (NR)	NR
								Pincer; tonnis angle	< 0°	31	NR	46 (NR)	NR
Pincer; cross over sign	Presence of cross over sign	25	NR	37 (NR)	NR								
Gerhardt 2012 ¹³¹ USA	Athletic population. Radiographs performed for routine preseason screening at 4 football teams	Participants	95 (75, 20)	NR	25 (NR)	NR	AP radiograph	Pincer; cross over sign	Presence of cross over sign	NR	22	NR	23 (27, 10)
Lahner 2014 ¹³⁰ Germany	Athletic population; semi professional and amateur male footballers.	Participants and hips	44 (44,0)	88 (88,0)	23 (18-30)	Presence of hip pain NR. Mean values for Hip Outcome scores 97 for subjects and 99 for controls. .	MRI, 3 o'clock	Cam; alpha angle	> 55°	Subjects 21 Controls: 13	Subjects: 13 Controls 9	Subjects: 48 (NA) Controls: 30 (NA)	Subjects: 59 (NA) Controls 40 (NA)

Lahner 2014 ¹³⁴ Germany	Athletic population: track and field athletes and controls	Participants and hip	44 (22,22) subjects: 22 controls: 22	88 (44,44) subjects: 44 controls: 44	23 (18-32)	Presence of hip pain NR. Mean values for Hip Outcome scores 98 for subjects and 99 for controls. .	MRI, 3'clock	Cam; alpha angle	> 55°	Subjects: 15 Controls: 1	Subjects: 11 Controls: 1	Subjects: 34 (27, 41) Controls: 2 (NR)	Subjects: 50 (NR) Controls: 5 (NR)
							MRI, coronal plane	Pincer; centre edge angle	> 40°	Subjects: 0 Controls: 2	Subjects: 0 Controls: 2	Subjects: 0 Controls: 2 (0, 2)	Subjects: 0 Controls: 4.5 (0, 4.5)
Tak 2015 ¹³² Netherlands	Athletic population; Professional first team footballers from 2 Dutch clubs.	Participants and Hip	63 (63, 0)	126 (126, 0)	23 (18-38)	NR	AP and frog lateral radiographs	Cam; alpha angle	> 55°	40	62	49 (n/a)	64 (n/a)
Johnson 2012 ⁹⁶ USA	Athletic population; former high level youth soccer players and age and sex matched controls who did not participate in sport above a recreational level. No history of hip disorders	Participants	100 (50, 50)	NR	NR (18-30)	All participants asymptomatic	Frog lateral radiographs	Cam; alpha angle	> 55°	NR	Subjects 24, Controls 22	NR	Subjects 48 (60,36), Controls 44 (56,32)
Kolo 2013 ³³ Switzerland	Athletic population; Professional ballet dancers and asymptomatic age and sex matched non dancer controls.	Hips	NR	87 (0, 87)	25 (18-36)	Controls hips all asymptomatic. Mixture of asymptomatic and symptomatic dancers hips	MRI, around the axis of femoral head neck junction	Cam; alpha angle	> 55°	Subjects 1 Controls 0	NR	Subjects 2 (NA) Controls 0 (NA)	NR
Larson 2013 ⁹⁷ USA	Athletic population; male collegiate American football players	Participants and hips	125 (125, 0)	239 (239, 0)	NR- USA college students	75/ 239 hips symptomatic	AP and cross table lateral radiographs	Cam; alpha angle	> 55°	155	94	65 (n/a)	75 (n/a)
							AP radiograph	Pincer; coxa profunda	Presence of coxa profunda	6	5	2.5 (NA)	4 (NA)
								Pincer; acetabular protrusio	Presence of acetabular protrusio	1	1	0.4 (NA)	0.8 (NA)
								Pincer; cross over sign	Presence of cross over sign	154	89	64 (NA)	71 (NA)
Pincer; ischial spine sign	Presence of ischial spine sign	108	70	45 (NA)	56 (NA)								
Mariconda 2014 ¹³³ Italy	Athletic population; Capoeira (martial arts) competitors	Hips	NR	48 (28, 20)	32 (25-42)	7/48 hips symptomatic	AP and frog lateral radiographs	Cam; alpha angle	> 50°	44	NR	92 (NR)	NR
									> 60°	22	NR	46 (NR)	NR

							AP radiograph	Pincer; centre edge angle	> 39°	2	NR	8 (NR)	NR
							AP radiograph	Pincer; tonnis angle	< 0°	3	NR	6 (NR)	NR
							AP radiograph	Pincer; cross over sign	Presence of cross over sign	16	NR	33 (NR)	NR
Nepple 2012 ⁸² USA	Athletic population; male collegiate American football players	Hips	NR	123 (123, 0)	23 (20-25)	All participants symptomatic but not attributed to intra articular pathology	AP and frog lateral radiograph	Cam; alpha angle	> 63°	52	NR	42 (NA)	NR
							AP radiograph	Pincer; centre edge angle	> 39°	5	NR	4 (NA)	NR
								Pincer; tonnis angle	< 0°	25	NR	20 (NA)	NR
								Pincer; cross over sign	Presence of cross over sign	88	NR	72 (NA)	NR
						AP radiograph	Pincer; ischial spine sign	Presence of ischial spine sign	87	NR	71 (NA)	NR	
Abbreviations: NR= not reported. NA= not applicable. MRI = magnetic resonance imaging. CT = computerised tomography. AP = anteroposterior								Light shading = measure of pincer morphology			Dark shading = measure of cam morphology		

2.5 Discussion

The primary objective of this review was to describe the point prevalence of cam and pincer morphology in the general population. I found no general population-based studies reporting prevalence estimates for cam or pincer morphology. Thirty-eight of the included studies were subject to a high risk of bias, and there was substantial clinical heterogeneity preventing meta-analysis.

When assessed for risk of bias the included studies lacked external validity, as the populations they assessed were not representative of the general population. In addition to lacking external validity thirty-four studies did not sample populations that were representative of their 'target' population; these studies also lacked internal validity. These sources of bias make it difficult to generalise the point prevalence reported in any one study across the wider population.

Few of the included studies used the same case definitions for either cam or pincer morphology. Despite clinicians becoming increasingly familiar with the concept of cam morphology there does not appear to be any consensus on how best to define it.^{61,136} Some included studies also used a different case definition for males and females.^{98,110,112,113} These definitions were based on work by Gosvig et al who suggested a different α angle cut off value for normal (males $\leq 68^\circ$ females $\leq 50^\circ$), borderline (males $69-82^\circ$, females $51-56^\circ$) and abnormal (males $\geq 83^\circ$ females $\geq 57^\circ$) head neck junctions.⁶³ Gosvig et al chose these definitions based on the normal distribution of α angles and standard deviation of the measures in the population assessed in their study. While potentially useful as a descriptive measure I do not believe these thresholds are a helpful definition when trying to establish disease, as the thresholds are determined by statistical not clinically relevant methods.

While cam morphology describes a single shape characteristic, pincer morphology is more complex. This can be appreciated from the number of different measures and signs ($n=11$) and what they are attempting to characterise. The measures of pincer morphology broadly fit into two sub groups;

measure of global over coverage and measures of focal over-coverage/ acetabular retroversion. However there is no single sign or method of determining the presence of pincer morphology. Of the eleven measures of pincer morphology (see Table 4), nine are made on an AP pelvic radiograph. Of those nine measures, seven are prone to errors of pelvic rotation and tilt.¹³⁷

The included studies used a variety of imaging modalities including plain radiographs, CT and MR, and taking measurements in different planes. For example α angles at different positions on the femoral neck. The included studies by Hack et al, Mariconda et al and Omoumi et al demonstrated how the prevalence estimates of cam morphology changes based on the case definition used.^{94,125,133} A higher prevalence was found when using a lower α angle cut off value and measuring at the 1:30 o'clock. Cam morphology is thought to occur more frequently at the anterosuperior (1:30 o'clock) portion of the femoral head neck junction.^{16,138,139} Rakhra et al performed an MR imaging analysis of patients with cam morphology, 54% of patients had normal α angles at 12 and 3 o'clock but elevated α angles in the 1-2 o'clock positions.¹³⁸ Plain radiographs which are only able to make single α angle measurements, are therefore likely to underestimate the prevalence. Cross sectional imaging, that can measure at multiple points around the neck, is likely be more sensitive but without a loss of specificity.¹⁴⁰ A similar issue is likely to occur in the assessment of pincer morphology, especially when measuring for subtle forms of focal over-coverage. There were two measures of pincer morphology made on cross sectional imaging. Both did so on a single view; the mid point of femoral head on axial, and axial oblique planes respectively. An improved method of measuring pincer morphology may be to make assessments on multiple reconstructions around an axis, as was performed when measuring α angles around the axis of the femoral neck.

Despite the use of multiple different diagnostic criteria for cam and pincer morphology, the diagnostic utility of each is poorly understood and reported. Sutter et al have assessed the diagnostic utility of α angles and cam morphology and reported a 60° threshold measured at the 1:30 o'clock position offered a

sensitivity of 72% and a specificity of 76%. This study was biased in the selection of the 'gold standard' cases, which all required a α angle greater than 55°. Only Omoumi et al used the case definition proposed by Sutter et al.¹²⁵ With respect to pincer morphology the diagnostic utility of various measures is unknown in the setting of pincer type FAI syndrome.

One of the secondary objectives of this systematic review was to assess the relationship between hip shape and hip pain and establish the point prevalence of FAI syndrome. No studies reported the prevalence or incidence of FAI syndrome. However, four studies reported the association of hip shape and hip pain or hip related quality of life.^{97,98,123,133} The results were slightly conflicting with the studies of subgroups of the general population reporting no association (n= 3620 and 45 participants) and the studies of athletes reporting an association between cam morphology and hip pain (n= 125 participants and 45 hips). Given the low number of studies and the differing methodology it is hard to draw conclusions. Tsitskaris et al, assessing a subgroup of the general population, attempted to show an association with only 45 subjects using a chi squared test, their results could be prone to a type 2 error. However this is unlikely in the study by Gosvig et al with 3620 subjects. Another interpretation of the conflicting results in the different populations is that subjects competing in sport are more likely to develop symptoms in the presence of cam morphology than those in the general population. Theoretically this is possible given that sportsman are more likely to vigorously load their hips and use the limits of their range of motion. Without more studies, with consistent methodology it is not possible to establish a definitive conclusion. One of the excluded studies in this systematic review was a follow up of the subjects assessed by Hack et al.⁹⁴ This study reports that the relative risk of developing hip pain was 4.3 (95% CI 2.3-7.8) when cam deformity (α angle > 50.5° at 3 o'clock) was present.¹⁴¹

Another secondary objective of this systematic review was to assess differences in sub groups of the general population. I was unable to confirm whether cam or pincer morphology is more prevalent in athletes, partly due to the high degree of heterogeneity in study design and methods. It may be that different groups of

athletes have differing prevalence rates dependent on the sport. For example the difference between the track and field competitors or footballers assessed by Lahner et al; where there did appear to be a higher prevalence of cam morphology, whilst for the ballerinas assessed by Kolo et al; where there was not.^{33,130,134}

The sub group analysis of males and females did not identify a difference in the prevalence of pincer morphology. All studies that reported prevalence data by gender, using the same criteria, reported a higher prevalence of cam morphology in males. This may be due to different environmental exposures or a genetic influence. The development of cam morphology is associated with impact sports in adolescence, during this time the rates of physical activity in females is lower than that of males.⁸⁸ The development of cam morphology is also associated with subjects' genome, as demonstrated in the SibKids study.¹⁴² A combination of these two factors may explain the higher prevalence in males.

This systematic review has a number of limitations. Meta analysis was not possible in this review due to the high risk of bias and lack of homogeneity with respect to study population and case definitions applied. Five studies were excluded as they failed to report the results using a single measure; instead combining various different measures. Inclusion of these is unlikely to have affected the overall results of this review; none of the excluded studies were general population based, they used a range of different measures and the prevalence estimates were wide ranging. I also excluded studies that included participants aged less than 18 years, because of suggestions in the literature that the shape of the proximal femur can change in adolescence.^{85,86} This criterion meant excluding six studies reporting the prevalence of cam morphology in adolescents and adolescent athletes.^{85,86,95,143-145} This exclusion seems justified as these six studies report changing prevalence of cam morphology throughout development. However, three of these studies do report that cam morphology is more common in certain adolescent athletes compared to controls.^{85,95,143}

Whilst further research to determine the true prevalence of cam and pincer morphology is required the methods and criteria to define their presence must be agreed first. A method with a favourable diagnostic utility should be selected. Once the method for identifying cam and pincer morphology is chosen, the prevalence in the general population and in selected sub groups can be determined. The modified risk of bias tool for prevalence studies can assist in ensuring methodological rigour when designing such a study.¹⁰¹

2.6 Reflections

This chapter has provided me with opportunities to develop my research skills by understanding how to critically appraise the literature. The processes I have been through have also led me appreciate some of the nuances in understanding epidemiology in a wider context, not just in the setting of FAI syndrome; such as understanding samples, units of analysis, bias and definitions of disease. The chapter has stimulated me to conduct further research in areas where I felt there were deficiencies. Through my reflections, I have tried to document this learning.

At the time of planning this chapter, I intended that it would provide a springboard for my thesis. By answering a relatively simple question, I could move on to answering other research questions; such as whether surgery altered cartilage quality. In reality I found the results and the subsequent discussion led me to explore this area of research further.

I chose this research question as to understand FAI syndrome and its natural history it seemed fundamental to identify the 'at risk' population. I had read a number of articles that attempted to describe the prevalence of cam and pincer morphology but they provided wide-ranging estimates. Furthermore I had encountered the idea that athletes were more likely to have cam morphology and FAI syndrome but I wasn't certain if this stood up to scrutiny.

I choose to conduct this study as a systematic review. The PRISMA statement provides a checklist when establishing my methods for conducting a systematic review; a process I have followed.¹⁰⁰ I was advised by one of the co-authors (RB) of the accompanying published manuscript to follow the structure set out in reviews published in the Cochrane library. Part of conduct of a systematic review is an assessment of included studies risk of bias. When planning this review I considered a number of methods of achieving this; the GRADE system, the Newcastle Otowa quality scale (NOS) and the modified risk of bias tool for prevalence studies.^{101,146,147} Having reviewed these three tools I felt the most appropriate for this review was the modified risk of bias tool for prevalence studies. The GRADE system and the NOS were not as specific for rating prevalence studies.

When planning and considering this chapter I felt that cam morphology should be defined using an α angle, measured on cross sectional imaging, with a threshold value of 55° . I had at that stage not fully appreciated the issues with where on the femoral neck that measurement ought to be made. I had no reason to support this definition over any other and I sought studies that would reinforce my own bias. With respect to pincer morphology I thought CEAs were appropriate, although I believed a measure using cross sectional imaging had to be superior to an AP radiograph. At this stage of planning, despite not having completed searches, I was enthusiastic about conducting a meta-analysis. This would provide me with a 'definitive' prevalence estimate, allowing me to draw comparisons with different populations (e.g. athletes). When planning to conduct a meta-analysis I had initially intended to include only studies that assessed subjects with α angles, on cross sectional imaging, and that used a 55° for cam and a centre edge angle of $>39^\circ$ for pincer. This was before I completed my searches and appreciated some of the nuances to study design.

As I began selecting studies for inclusion, I realised that there were a wide range of populations being assessed, most of which were not truly representative of the general population. It was only when using the 'modified risk of bias tool' that I appreciated many of the sampling errors, in studies I had otherwise considered relatively robust. Reading the included manuscripts, I also noted the wide range of

different case definitions. There seemed little justification for any one definition over any other. I also appreciated the importance of consistency in the unit of analysis. It became very difficult synthesising the data from some studies where it was apparent that the authors had not considered this issue e.g. reporting participants affected when it was apparent that actually they were discussing hips affected.

As I gained an appreciation of these issues I realised that it would be inappropriate to attempt meta-analysis (some of my early attempts demonstrated I^2 statistics of 98%!)), without first setting out some rules. I therefore redesigned my systematic review. I decided to look to assess study 'clinical' heterogeneity first. This meant including studies in a meta analysis that assessed the same target population and used the same diagnostic methods. I also only included studies that were not rated at a high risk of bias. Setting these rules meant no studies were suitable for meta-analysis. I was interested to observe that a similar review was published that did perform meta-analysis.⁸³ The authors of this review did not seem to appreciate the issues of case definition, of populations sampled and of unit of analysis.

Having highlighted these issues in the systematic review I realised that I could not simply answer the 'simple' research question as I had intended. Nor could I glaze over some of the issues I had identified. Therefore, I devoted time and chapters 3, 4, 5 and 6 to answer what case definitions should be used, what the prevalence is in the general population and in an athletic population.

In hindsight, the objectives I set in this review were too broad. The search and study selection strategies were designed to answer the primary objectives. In answering the primary questions I began to think of a number of other questions the included manuscripts could address; including the relationship between hip shape and pain. I therefore attempted to answer the secondary objectives. In order to answer these questions I ought to have redesigned the search strategy. For example assessing the relationship between hip shape and hip pain I should have included other search terms such as "hip pain" or "hip related quality of life" and expanded the types of

studies I selected. It also become more complex trying to address more than one research question when selecting studies for inclusion during the screening process.

*At the time of writing this chapter for my thesis I was able to review the work that I had successfully published on this topic in *Osteoarthritis and Cartilage*.¹⁴⁸ At the time of publishing, I was pleased with the work. With hindsight I think now I would have written a different article for publication. In the publication I only assessed cam morphology, this was for reasons of word counts and complexity in a published manuscript. This size of this chapter is itself testimony to how large such a thorough systematic review needs to be. In assessing cam morphology in the publication, I choose to only include articles that measured the α angle; with hindsight, this was a mistake. I should have assessed all methods of determining the presence of cam and not just the method that I conceived was superior. Ultimately, as I have demonstrated in this chapter, the results remain unchanged.*

In conclusion, through the work I have conducted in this chapter I have developed my understanding of conducting systematic reviews and critically appraising epidemiological research. The chapter has stimulated me to conduct further research to better define FAI syndrome, cam and pincer morphology and report their prevalence in the general population. This work is reported in chapters 3, 4 and 5.

3 FAI Consensus Meeting

In this chapter I present the design and results of an international multidisciplinary consensus meeting on femoroacetabular impingement syndrome. I focus on discussions that relate to how femoroacetabular impingement syndrome should be defined and diagnosed.

Declarations

I received support in designing and convening the consensus development meeting from Damian Griffin, John O'Donnell and Kim Bennell. The results of the chapter reflect the opinions of the consensus panel members.

This chapter has been published:

Griffin DR, Dickenson EJ, O'Donnell J, Awan T, Beck M, Clohisy JC, Dijkstra HP, Falvey E, Gimpel M, Hinman RS, Hölmich P. The Warwick Agreement on femoroacetabular impingement syndrome (FAI syndrome): an international consensus statement. *British Journal of Sports Medicine*. 2016. 50(19):1169-76.

This chapter has been presented:

Title: FAI Syndrome. Presenter: E Dickenson Event: Royal College of Radiologists Annual Scientific Meeting, London, September 2016.

This research was supported by the National Institute of Health Research (Health Technology Assessment Programme Grant number 13/103/02) and the International Society of Hip Arthroscopy.

3.1 Introduction

In chapter 2 I reported that the prevalence of cam and pincer morphology was unknown partly due to the lack of agreed case definitions. During the systematic review I observed a number of authors were using terms such as ‘asymptomatic FAI’ and “radiological FAI”.^{94,113,126} I interpret the authors use of these terms, as them referring to subjects with cam or pincer morphology but with no symptoms. The use of such terms creates ambiguity. There use interchangeably with FAI in published literature and at conferences, and the lack of a consistent definition for cam and pincer morphology suggests there is uncertainty regarding the terminology, definition and diagnostic criteria of FAI syndrome.¹⁴⁹ Concerns also exist about the rapid increase in the number of patients undergoing surgery for a condition that until 2003 was not widely recognised. Are clinicians over diagnosing the disorder? What criteria must a patient meet in order to be diagnosed and potentially undergo surgery; is it simply the presence of an apparently common x-ray finding? These issues have implications on healthcare funders who are concerned to see their budget for treating a previously *unrecognised* condition ballooning, when little evidence regarding the efficacy of those treatments or the epidemiology of the disorder exists.^{71,149,150}

In this thesis I aim to establish the point prevalence of cam and pincer morphology in the population. However, before I can do this I must address these fundamental questions of what FAI is and how should it be diagnosed. I chose to answer these questions using consensus development methodology.

The Health Technology Assessment (HTA) programme of the National Institute of Health Research (NIHR) has outlined methods of consensus development.¹⁵¹

These include:

1. Delphi Study

This is a method by which participants are sent questionnaires, which seek their views. The organisers collated the responses, summarise them and send the summary back to participants. Participants have the opportunity to revise their views based on group feedback. The process is repeated a number of times.¹⁵¹

Delphi studies were originally used in forecasting the development of technology. They are a statistical method to improve individual estimates by combining estimates from different experts. Participants never directly interact, which reduces the chance of dominant personalities influencing the group consensus. Conversely the benefits of direct interaction and discussion are lost.¹⁵¹

2. Nominal Group Technique

The nominal group technique was introduced by Delbecq.¹⁵² It is a structured group interaction to develop ideas. In this process group member individually propose ideas, each of which is considered, discussed and developed in turn. The group are then able to vote, anonymously, on the ideas generated. The nominal group technique has been modified to include individual pre meeting questionnaires, the results of which are discussed in the group meeting, individuals then respond to each idea by a post meeting questionnaires.¹⁵¹

3. Consensus development conference

A consensus development conference involves an open meeting, usually held over a number of days, where experts present evidence on the topic of interest. Following the open meeting a panel is convened to deliberate over the evidence and reach a consensus. Discussions at both the open and the closed meetings are chaired. This type of consensus development is derived from the concept of a legal trial, where a jury hears evidence and privately deliberates to reach a consensus.¹⁵¹

In this chapter I present the methodology and outcomes of the consensus development conference that I organised (with supervisors help) and chaired.

3.2 Objectives

By means of a consensus development conference I will:

- Define FAI
- Define how FAI should be diagnosed, considering:
 - Symptoms,
 - Clinical Signs,

- Radiological criteria.

3.3 Methods

A consensus development conference was set up to answer a number of questions relating to FAI syndrome using established consensus development methodology.¹⁵¹

In this chapter I shall focus on the following questions, directly relevant to this thesis, which the conference addressed:

- What is FAI syndrome?
- How should FAI syndrome be diagnosed?

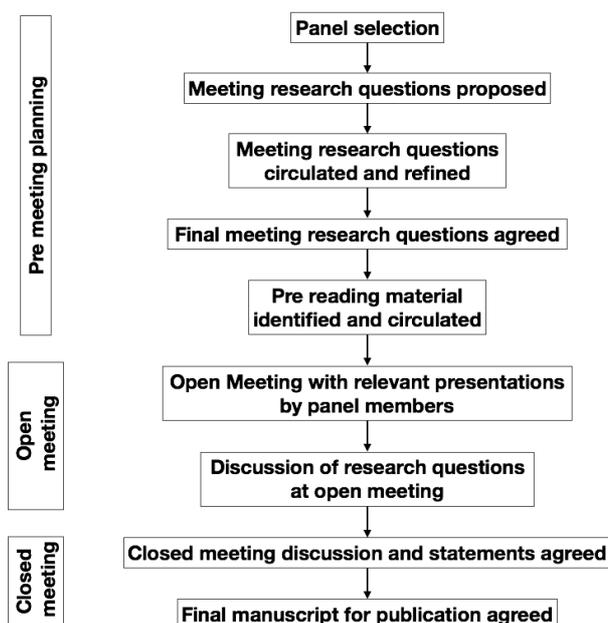
The consensus development conference also answered the following questions that I did not feel were directly relevant to this thesis:

- What is the appropriate treatment of FAI syndrome?
- What is the prognosis of FAI syndrome?
- How should someone with an asymptomatic hip with cam or pincer morphology be managed?
- Which outcome measures should be used to assess treatment for FAI syndrome?
- What future research needs to be conducted?

The outcomes of these questions can be read in the published consensus statement.⁷⁰

The consensus conference was conducted in three phases; pre meeting preparation, an open meeting and a closed consensus development conference; see flow diagram in Figure 9.

Figure 9 Consensus Meeting Flow Diagram



3.3.1 Pre Meeting Preparation

DG and I invited representatives from a range of professions and specialties to join the consensus panel. We included sports and exercise medicine physicians, physiotherapists, orthopaedic surgeons, an epidemiologist, health economist and radiologist. We invited people who were known to have a research interest and clinical practice in FAI, and asked professional organisations with a known interest to nominate suitable people (International Society for Hip Arthroscopy, International Federation of Sports Physical Therapy, and American Medical Society for Sports Medicine). We aimed to have representation from around the world, and deliberately chose people who we knew to hold disparate views, representing as wide a spectrum of opinion as possible. In total 22 expert clinicians and academics, and one patient, from nine countries and five specialties, participated in the process; see Table 7. Relevant literature for each of the research questions was identified, with a preference for systematic reviews and seminal articles and circulated to panel members; see Table 8.

Table 7 Panel members

Panel Member	Nationality	Specialist Area	Justification
Dr Rintje Agricola	Netherlands	Epidemiologist	Leading epidemiologist in the field of FAI and has published numerous articles on the natural history of cam and pincer morphology.
Dr Tariq Awan	USA	Sports Physician	Nominated to attend by the American Medical Society for Sports Medicine.
Prof Martin Beck	Switzerland	Orthopaedic Surgeon	Professor of Orthopaedic surgery, high volume open hip preservation surgeon. One of the original authors describing FAI.
Prof John C. Clohisy	USA	Orthopaedic Surgeon	Previous convenor of a consensus meeting regarding FAI in the USA.
Dr H. Paul Dijkstra	Qatar	Sports Physician	Academic sports physician. Previous convenor of consensus meeting of groin pain in athletes. Favours conservative treatment of FAI.
Dr Eanna Falvey	Ireland	Sports Physician	Sports physician and team doctor for Ireland and British and Irish Lions rugby. Balanced view of diagnosis and treatments for FAI.
Mo Gimpel	UK	Physiotherapist	Medical director for Southampton football club. Conducting research into development of cam morphology. Known to favour physiotherapy to treat FAI.
Prof Damian Griffin	UK	Orthopaedic Surgeon	High volume hip arthroscopist, conducting clinical trials in FAI. Part of core group convening meeting. My PhD supervisor.
Prof Rana Hinman	Australia	Physiotherapist	Professor of physiotherapy, conducting clinical trials in FAI.
Prof Per Hölmich	Denmark	Orthopaedic Surgeon	Academic orthopaedic surgeon known to have a balanced view on the diagnosis and treatment of FAI.
Dr Ara Kassarian	Spain	Radiologist	Radiologist with interest in diagnostic imaging of FAI.
Dr Hal D Martin	USA	Orthopaedic Surgeon	Hip surgeon and committee member of International Society of Hip Arthroscopists where he oversees research.
Dr RobRoy Martin	USA	Physiotherapist	Academic physiotherapist; nominated attendee for International Federation of Sports Physical therapy
Dr Richard C Mather	USA	Orthopaedic Surgeon and health economist	Academic hip surgeon. Interest in research into cost effectiveness and health economics.
Dr Marc J Philippon	USA	Orthopaedic Surgeon	High volume hip arthroscopist for FAI, widely published in the area. Known to hold pro-surgical views.
Michael Reiman	USA	Physiotherapist	Academic physiotherapist, publishes on utility of clinical examination in assessment of FAI. Critical of over diagnosis and over treatment of FAI.
Amir Takla	Australia	Physiotherapist	Academic physiotherapist with interest in postoperative rehabilitation. Previously undergone FAI surgery himself.
Dr Kristian Thorborg	Denmark	Physiotherapist	Academic physiotherapist, published on utility of examination features of FAI. Known to hold views that are critical of surgeons he sees as over diagnosing and over treating patients.
Sally Walker	UK	Patient representative	Patient and public representative. Sally had previously undergone FAI surgery.
Dr Adam Weir	Netherlands	Sports Physician	Academic sports physician, deputy editor of BJSM. Previous convenor of consensus meeting of groin pain in athletes.
Dr John O'Donnell	Australia	Orthopaedic Surgeon	High volume hip arthroscopist and previous president of the International Society of Hip Arthroscopy.
Prof Kim Bennell	Australia	Physiotherapist	Professor of physiotherapy, conducting clinical trials in FAI. Part of core group convening meeting.

Table 8 Manuscripts Circulated to panel members in advance of the meeting.

Title	Year	First author and reference	Justification
Femoroacetabular impingement: a cause for osteoarthritis of the hip	2003	Ganz ⁴	First manuscript to describe FAI.
Femoroacetabular Impingement Surgery Is on the Rise—But What Is the Next Step?	2016	Reiman ¹⁵³	A manuscript that questions the diagnostic criteria for FAI.
Physical impairments in symptomatic femoroacetabular impingement: a systematic review of the evidence	2016	Freke ¹⁵⁴	A recent systematic review that identifies evidence for physical impairments in patients with FAI syndrome.
What is Femoroacetabular impingement?	2016	Agricola ¹⁵⁵	A manuscript that questions the definition of FAI syndrome.
Diagnostic accuracy of clinical tests for the diagnosis of hip femoroacetabular impingement/labral tear: a systematic review with meta-analysis	2014	Reiman ¹⁵⁶	A systematic review of the accuracy of clinical examination findings.
Prevalence of Cam Hip Shape Morphology: A Systematic Review	2016	Dickenson ¹⁴⁸	Systematic review presented in chapter 2. Questions the radiographic diagnostic criteria and the prevalence of cam morphology in the general population.
Diagnostic imaging of femoroacetabular impingement	2013	Nepple ⁶¹	This is the paper from a previous consensus meeting relating to diagnostic imaging.
Clinical diagnosis of femoroacetabular impingement	2013	Nepple ¹⁵⁷	This is the paper from a previous consensus meeting relating to the clinical diagnosis.
How useful is the alpha angle for discriminating between symptomatic patients with cam-type femoroacetabular impingement and asymptomatic volunteers?	2012	Sutter ¹⁵⁸	This manuscript attempts to scientifically define the diagnostic criteria for cam morphology.
Comparison of MRI alpha angle measurement planes in femoroacetabular impingement	2009	Rakhra ¹³⁸	This manuscript raises concerns about defining cam morphology on AP radiographs alone.

3.3.2 Open Meeting

Panel members gave presentations at *Sports Hip 2016*

(www.sportshipsurgery.org), an open meeting held in the UK on the 27-28th June 2016. 120 international delegates from a range of clinical backgrounds (surgeons n= 47, physiotherapists n=54 and sport and exercise medicine doctors n=7, other n=12) familiar with managing young adult hip pathology attended the conference. Panel members' presentations explored each topic with an emphasis on the highest levels of evidence, from systematic reviews and randomised controlled trials where available. After each presentation, DG chaired an open discussion where all delegates and panel members discussed each topic.

3.3.3 Consensus Development Meeting

I chaired the closed consensus development meeting to formulate the agreement statements on the 29th June 2016 at the University of Warwick.

Prior to the meeting DG, KB, JOD and I prepared proposed statements for each topic; see Table 9. I facilitated a structured discussion where we amended the proposed statements leading to a final wording for consideration. Panel members then voted on each proposal on a Likert scale of 0 to 10, where 0 reflected complete disagreement, 5 neither agreement nor disagreement, and 10, complete agreement. Levels of agreement were summarised with mean scores and 95% confidence intervals. Discussions continued until a mean score of greater than 7.5 was reached, or until I deemed that no further compromise could be found. Other international multidisciplinary consensus meetings in musculoskeletal medicine have used similar methods to score the level of agreement.¹⁵⁹

Table 9 Proposed answers for each topic

Research Question	Draft answer
What is FAI syndrome?	FAI syndrome is a clinical disorder with a characteristic triad of symptoms, clinical signs, and imaging findings. It arises as a result of painful premature contact between the proximal femur and the acetabular rim.
How should FAI syndrome be diagnosed?	<p>The following symptoms, signs and imaging findings should be present in order to diagnose FAI syndrome:</p> <p>Symptoms of FAI syndrome: The primary symptom of FAI syndrome is pain, usually reported arising from the hip or groin. Pain referred to the back, buttock or thigh may be encountered which may be confirmed with aid of an intra articular local anaesthetic injection. Pain is frequently exercise related that improves with rest. Other symptoms may include clicking, catching, locking, restrictive range of motion and giving way.</p> <p>Clinical Signs: A restricted range of motion, most often internal rotation in flexion, with reproduction of typical pain is encountered in FAI syndrome. One or more impingement tests (Flexion adduction internal rotation, flexion abduction internal rotation and flexion abduction external rotation) are usually positive.</p> <p>Diagnostic Imaging: AP radiographs should be performed to exclude other causes of hip pathology e.g. Osteoarthritis. AP radiographs are usually insufficient to fully characterise the morphology of the hip. An AP radiograph may be supplemented with femoral neck views. However in order to fully characterise the hip morphology cross sectional imaging is required. Cam morphology can be identified by an alpha angle greater than 55° in the antero-superior portion of the head neck junction. A CEA greater than 39° and a positive cross over sign are used as measures of pincer morphology.</p>

3.4 Results

The results of the consensus meeting are presented as the agreed statements (with the corresponding levels of agreements) and a summary of the panel's discussions.

3.4.1 What is FAI syndrome?

Agreed Statement:

FAI syndrome is a motion-related clinical disorder of the hip with a triad of symptoms, clinical signs, and imaging findings. It represents symptomatic premature contact between the proximal femur and the acetabulum.

Level of agreement: mean score 9.8 (95% CI 9.6-10)

Summary of the Panel's Discussion

The panel discussed the origin of the diagnosis of femoroacetabular impingement. Ganz et al described it as a condition of 'abnormal contact that may arise as a result of either abnormal morphologic features... or as a result of subjecting the hip to excessive and supraphysiologic range of motion'.⁴ Sankar et al further developed this definition,¹⁶⁰ describing 'five essential elements':

- Abnormal morphology of the femur and/or acetabulum;
- Abnormal contact between these two structures;
- Especially vigorous supraphysiologic motion that results in such abnormal contact and collision;
- Repetitive motion resulting in the continuous insult;
- The presence of soft-tissue damage.

The panel felt that these definitions did not sufficiently emphasise patients' symptoms. Ambiguity as to the role of symptoms in making a diagnosis of FAI has led to the introduction of new terms such as 'asymptomatic FAI' or 'radiological FAI',^{94,105,161} apparently to describe hip morphologies rather than a clinical disorder.¹⁴⁸ The panel agreed that this has created confusion when trying to define the clinical disorder.

To make clear the need for symptoms to be present, the panel proposed the new term 'femoroacetabular impingement syndrome', or 'FAI syndrome'.¹⁶² They considered other terms, e.g. hip impingement syndrome, but preferred FAI syndrome as this did not include extra-articular hip impingement such as ischio-femoral or greater trochanteric impingement. They considered whether

'syndrome' might apply a negative label to patients, but the expert patient member of the panel did not feel this would be the case.

To ensure there is a distinction between patients with FAI syndrome and those with cam or pincer morphology but no clinical disorder, the panel recommended certain terminology be used while we cease to use other terms that were considered confusing (see Table 10).

Table 10 Agreement on terminology relating to femoroacetabular impingement

Recommended terminology	Terminology to be avoided
Cam morphology	Symptomatic FAI
FAI syndrome	FAI morphology
Pincer morphology	Asymptomatic FAI
	Radiographic FAI
	Deformity, abnormality or lesion when referring to cam or pincer morphology
Level of agreement: mean score 10 (95% CI 9.8-10)	

3.4.2 How should FAI syndrome be diagnosed?

Agreed Statement

Symptoms, clinical signs and imaging findings must be present to diagnose FAI syndrome.

Level of agreement: mean score 9.8 (95% CI 9.6 to 10).

Symptoms

The primary symptom of FAI syndrome is motion- or position-related pain in the hip or groin. Pain may also be felt in the back, buttock or thigh. In addition to pain, patients may also describe clicking, catching, locking, stiffness, restricted range of motion or giving way.

Level of agreement: mean score 9.5 (95% CI 9.0-10)

Clinical Signs

Diagnosis of FAI syndrome does not depend on a single clinical sign; many have been described and are used in clinical practice. Hip impingement tests usually

reproduce the patient's typical pain; the most commonly used, flexion adduction internal rotation (FADIR) is sensitive but not specific. There is often a limited range of hip motion, typically restricted internal rotation in flexion.

Level of agreement: mean score 9.9 (95% CI 9.7-10)

Diagnostic Imaging

An anteroposterior radiograph of the pelvis and a lateral femoral neck view of the symptomatic hip should initially be performed to obtain an overview of the hips, identify cam or pincer morphologies, and identify other causes of hip pain. Where further assessment of hip morphology and associated cartilage and labral lesions is desired, cross sectional imaging is appropriate.

Level of agreement: mean score 9.5 (95% CI 9.1-9.8)

Summary of Panel's Discussion

Symptoms

The panel felt the primary symptom of FAI syndrome was pain.⁴ However, they recognized the wide variation in the location, nature, radiation, severity and precipitating factors that characterise this pain. Most patients report pain in the groin or hip, but pain is also reported in the lateral hip, anterior thigh, buttock, knee, lower back, lateral and posterior thigh.¹⁶³ In FAI syndrome the panel agreed that pain is typically motion or position-related. They recognised that this encompasses a wide range of patients, from those who experience symptoms during or after vigorous activity (e.g. football), to those who have pain with a supra-physiological range of motion (e.g. dancers, gymnastics), to those who get symptoms despite leading a sedentary lifestyle (seated for long periods).^{4,163,164} The panel agreed that mechanical symptoms, such as clicking, catching, locking, giving way or stiffness are also reported by many patients with FAI syndrome.¹⁶³

The panel discussed the common problem of determining whether pain is really arising from the hip joint or from other structures in the groin and hip region. They agreed that image guided (X-ray or ultrasound) local anaesthetic injections are useful in helping to resolve this situation.^{165,166} Pain relief following an intra

articular local anaesthetic injection would support a diagnosis of FAI syndrome, when the other diagnostic criteria are met.¹⁶⁷

The panel agreed that in most patients who seek treatment for FAI syndrome, symptoms are not mild or subtle. They are often severe and limiting in everyday life. The panel felt that this is especially important because patients are usually young, economically active adults. Symptoms of FAI syndrome therefore lead to significant and lasting cost burden for society as well as being individually debilitating.¹⁶⁸

Signs

The panel discussed the need for a comprehensive hip and groin examination, as part of the determination of a diagnosis of FAI syndrome.¹⁶⁹

Many examination techniques and clinical signs for FAI syndrome have been described, but the panel agreed that there are several problems with the various examination features. Different clinicians apply and interpret clinical tests differently, with little consistency between professional groups or even among peers.^{169,170} Even when tests are well-defined, they have often been evaluated in populations with a high likelihood of a positive test,¹⁵⁶ so their performance in a different environment (such as primary care) is not known. The panel agreed that the most well-known test, the FADIR impingement test, is sensitive (usually positive when FAI syndrome is present), but not specific (often positive when FAI syndrome is not the correct diagnosis).¹⁵⁶ The evidence on hip range of motion in FAI syndrome is surprisingly contradictory,^{72,154} but the panel felt that on balance, FAI syndrome is associated with a restricted hip ROM.

The panel also recognised that abnormal movement patterns around the hip and pelvis are present in patients with FAI syndrome.^{72,75} These movement patterns, associated with FAI syndrome, may lead to pain or dysfunction in other regions, such as the spine, pelvis, posterior hip, or abdominal wall.⁷² Furthermore, muscles around the hip are frequently weak in patients with FAI syndrome.¹⁵⁴

The panel concluded that when FAI syndrome is suspected, it is important to examine gait, single leg control, muscle tenderness around the hip, and hip ROM including internal rotation in flexion and the FABER distance (flexion abduction external rotation). Impingement testing should be performed, and to be positive it must reproduce the patient's familiar pain. The panel also noted that it is essential to examine the groin for other structures that can produce similar pain.

Imaging Findings

The panel agreed that a morphological assessment of the hip is required in order to diagnose FAI syndrome; identifying cam or pincer morphology. Cam morphology refers to a flattening or convexity at the femoral head neck junction.⁴ Pincer morphology refers to either global or focal over-coverage of the femoral head by the acetabulum.⁴ The panel emphasised that their presence, in the absence of appropriate symptoms and clinical signs, does not constitute a diagnosis of FAI syndrome. The panel agreed that a substantial proportion of people in the general population are thought to have cam or pincer morphology.^{83,148}

The panel agreed that radiological assessment is best achieved initially with plain radiographs. An AP pelvic radiograph allows an overall assessment of the pelvis and hips, and exclusion of other painful conditions such as fracture, acetabular dysplasia and osteoarthritis. The panel agreed that ideally, this radiograph should be centered on the pubic symphysis, without rotation, and with neutral pelvic tilt.^{4,137} The shape of the acetabulum can be interpreted from this radiograph,⁴⁵ but visualising the shape of the proximal femur requires an orthogonal view of the femoral neck. A number of such views have been described such as the cross-table lateral, Dunn and frog laterals.¹⁷¹

The panel discussed the complexities in interpreting three-dimensional shapes from plain radiographs. For example, the spatial orientation of the acetabulum may be affected by the position of the pelvis. Posterior tilt increases in standing

position and the parameters that describe anterior and posterior acetabular coverage, which are important in describing pincer morphology, may change.^{172,173} Also, two orthogonal views of the femoral neck may not be sufficient to identify all instances of cam morphology.¹³⁸ The panel felt that in combination, these radiographs are only moderately sensitive for identifying the typical morphology of FAI syndrome, but are specific.¹³⁸

The panel agreed that morphology can be better characterised through cross-sectional imaging, either CT or MRI.^{138,174} This is particularly important if surgery is being considered. MR arthrography is usually more accurate than plain MRI to assess the labrum and articular cartilage.^{175,176} MRI may also identify other soft tissue lesions that may result hip or groin pain. The panel discussed the role of femoral neck antetorsion in FAI syndrome. They agreed that when performing cross-sectional imaging, limited images of the distal femoral condyles allows assessment of femoral torsion, while 3D reformatting of CT or radial MRI allow assessment of focal morphological abnormalities, particularly of the proximal femur.¹⁵⁸

The panel discussed the many different radiographic measures of cam and pincer morphology including α angle (cam), cross-over sign and centre edge-angle (pincer).^{62,67,177} Although some members of the panel suggested certain threshold values for α angles when determining the presence of cam morphology (RA: 60° measured on an AP radiograph,¹⁰³ AK: 55° measured in antero-superior portion of head neck junction,¹⁵⁸ HPD 63°, although unclear where this should be measured⁶¹), overall the panel were unable to recommend precise diagnostic values for any of the common measures to define cam or pincer morphology in routine clinical practice due to a lack of sufficient evidence supporting any one measure or threshold. They also recognised that impingement is the result of a complex interaction, during motion, between the acetabulum and femoral neck. They agreed that the depth, orientation and rim of the acetabulum, and the head-neck profile, neck angle and torsion of the proximal femur all vary in the general population. It is when a particularly unfavourable combination of these characteristics occur together, along with provocative movement or position, that

a patient may present with FAI syndrome. The panel agreed that at present it has not been possible to capture all of this in a single measurement or even a simple set of shape criteria.

3.5 Discussion

This consensus development conference was convened due to concerns that there was no unifying clear definition and diagnostic criteria for FAI syndrome.^{148,149,153,155,162} This consensus statement is intended to provide an agreed definition and diagnostic criteria for FAI syndrome. While some point to the simplicity of the statements, I find this reassuring.¹⁷⁸ The published consensus statement “The 2016 Warwick Agreement on FAI syndrome” has been endorsed by 25 clinical societies (see footnote ¹), suggesting it has achieved the aim of providing a consensus of opinion.⁷⁰

American Medical Society for Sports Medicine (AMSSM), Association of Chartered Physiotherapists in Sports and Exercise Medicine (ACPSEM), Australasian College of Sports and Exercise Physicians (ACSEP), Austian Sports Physiotherapists, British Association of Sports and Exercise Medicine (BASEM), British Association of Sport Rehabilitators and Trainers (BASRaT), Canadian Academy of Sport and Exercise Medicine (CASEM), Danish Society of Sports Physical Therapy (DSSF), European College of Sports and Exercise Physicians (ECOSEP), European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA), Finnish Sports Physiotherapist Association (SUFT), German-Austrian-Swiss Society for Orthopaedic Traumatologic Sports Medicine (GOTS), International Federation of Sports Physical Therapy (IFSPT), International Society for Hip Arthroscopy (ISHA), Groupo di Interesse Specialistico dell’A.I.F.I., Norwegian Association of Sports Medicine and Physical Activity (NIMF), Norwegian Sports Physiotherapy Association (FFI), Society of Sports Therapists (SST), South African Sports Medicine Association (SASMA), Sports Medicine Australia (SMA), Sports Doctors Australia (SDrA), Sports Physiotherapy New Zealand (SPNZ), Swedish Society of

Some of the issues addressed in the Warwick agreement were reviewed in 2012 when Clohisy and Kim organised a meeting in an attempt to design future research.^{61,157,160,179-182} Our consensus statement was intended to build on this work, and we were pleased John Clohisy was able to participate as a co-author and panel member. The first statement on the definition of FAI syndrome refers back to Clohisy's work, and the panel were circulated the relevant papers from his 2012 meeting in the pre reading material.^{61,157} Clohisy's 2012 meeting was not designed to produce a consensus statement in the same way as the Warwick agreement, nor did it use established consensus development methodology.¹⁵¹ Clohisy intended his meeting to summarise the literature on FAI with a view to establishing a direction for research. A criticism of that meeting was it mainly included American Orthopaedic Surgeons and so the opinions expressed were not truly representative of the international community assessing and treating these patients. With the Warwick Agreement, we made an effort to ensure we were inclusive of different interested parties with disparate views.

Consensus development methodology is increasingly used in the generation of new clinical guidelines.^{159,183,184} Of the three methods described by the HTA I chose a consensus development conference.¹⁵¹ I felt it would allow the presentation of literature to panel members; via reading material and podium presentations at the open meeting, and the expression of views from a wide audience (during the open phase of the meeting). A consensus development conference also allows face-to-face interactions and discussions about complex points between different experts in the field. These led me to form the opinion that this was the strongest method of establishing agreement, and that the level of agreement would be representative of and respected by the external community. I did not feel that other methods, such as a Delphi study or Nominal Group Technique, would be as efficient in achieving the same goals.

Exercise and Sports Medicine (SFAIM), Swiss Society of Sports Medicine (SGMS/SGSM), Swiss Sports Physiotherapy Association (SSPA) ¹

Consensus development conferences do have weaknesses. The participants included have a large influence on the outcome. DG and I intentionally chose a heterogeneous group of individuals from across the world, from different specialties, that included academics and clinicians, and who were recognised within their communities to hold disparate views. Choosing a heterogeneous group is recognised to improve the performance of the panel.¹⁸⁵⁻¹⁸⁷ The personal characteristics of panel members also influences outcome. Choosing a mix of members with strong and weak personalities could lead to the weaker personalities not being listened to.¹⁸⁸ It was the intention when inviting the panel that all members were senior academics and clinicians and would all be strong personality, although willing to listen to sound reason. Reflecting on the meeting there were certain members who were less influential on the discussions. These members were all from different groups; physiotherapist, patient representative and sports physician respectively.

One of the criticisms of the outcome of the agreement, when we sought endorsement from specialist societies prior to publication, was that the outcomes may have been different were the consensus conference conducted at a different meeting. I feel this criticisms is unfair, as we deliberately designed our meeting with the objective of representing the views of different specialists involved in managing FAI syndrome, from around the world. This view was expressed by a member of a group of orthopaedic surgeons not involved in the meeting. They felt that the outcomes would be more applicable if the consensus conference was held “at a large American orthopaedic meeting”. This would have led to over representation of American Orthopaedic surgeons and an under representation of other specialties. I was already conscious that there were a large number of North American Orthopaedic surgeons (n=4) on our panel. It is one of the true strengths of the Warwick agreement that it has international multidisciplinary input. The scale of the outputs can be measured by specialist societies representing surgeons, physiotherapists and sports medicine doctors from around the world who have endorsed the statement.

Despite the merits of the Warwick agreement, it has not furthered my aims to establish criteria to define the presence of cam and pincer morphology. The panel recognised the controversy regarding the radiological criteria needed to define the presence of cam and pincer morphology. They felt that the morphology of the hip is best characterised on cross sectional imaging. Despite discussions regarding threshold values of the various measures to determine the presence of cam and pincer morphology the panel were unable to agree. This was in part due to the lack of scientific evidence supporting any one measure or threshold, but also the panel's recognition that in clinical practice impingement is the result of a complex interaction during motion of the proximal femur and the acetabulum. While this pragmatic approach is reasonable in clinical practice it is unhelpful for epidemiological studies where precise criteria, with a known diagnostic utility, are required. Therefore, in order to define these criteria I will need to conduct original research to provide evidence as to the optimal criteria for defining cam and pincer morphology.

3.6 Conclusion

The consensus development conference has provided clear terminology and a definitive definition for FAI syndrome. The panel has defined how FAI syndrome should be diagnosed considering symptoms, clinical signs and radiological features. Despite recognising that diagnosis requires cam or pincer morphology to be present, the panel were unable to define how these should be objectively measured. While it is true that impingement is the result of a complex interaction during motion between the femoral neck and the acetabulum, this definition does not aid epidemiological research. In order to conduct further epidemiological research objective methods of determining the presence of cam or pincer morphology are required.

3.7 Reflections

In this chapter's reflections I consider what I have learnt through this piece of research and what I would have done differently given more time or resources. The work I conducted also provided me an opportunity to learn by observing others; such as the organisation required to set up an open meeting.

In trying to address this chapter's objectives I had to consider the different consensus development methodology. I had initially considered a Delphi study, selecting this design may have been a mistake. Without direct participant interaction, I think I may have missed the opportunity for panel members to address questions in a manner that provides meaningful results or conclusions. For example in a Delphi study identifying how to determine the presence of cam morphology I could have asked which method should be used, how it should be measured and which threshold values to use. This may have led to an answer, but it would not necessarily be supported by scientific fact, nor would it have unearthed some of the more fundamental underlying issues. In trying to establish how cam morphology should be defined the consensus development panel were able to agree that FAI syndrome was the result of a complex interaction, during motion that resulted from an unfavourable combination of the depth, orientation and rim of the acetabulum, and the head-neck profile, neck angle and torsion of the proximal femur. I am not sure that such an answer could be established using a Delphi study. I am aware that a researcher in the USA has attempted to define how we determine the presence of cam morphology with a Delphi study, but as far as I am aware, without success.

In addressing the chapter objectives I did not consider the nominal group technique. This method did not seem to adequately sample the opinions of workers in different specialties internationally. It was important that the wider community treating patients with FAI syndrome regarded the consensus statement as representative of their views. However, unintentionally the structure of the consensus development conference did possess a degree of nominal group technique. I arranged planning meetings for the consensus development conference between Damian Griffin, John O'Donnell, Kim Bennell and myself. Although we did not intentionally work within the rules of a nominal group technique this core team did share and develop ideas that steered the direction of the consensus development conference. Mixing

*consensus-building methodology can be appropriate in certain situations. A combination of the three techniques was used in developing Personalised Hip Therapy, the comparator to surgery in the FASHIoN trial.*⁷⁴

*In organising the consensus development conference we did not strictly follow the design set out in the HTA Journal.*¹⁵¹ *We used the design of other successful consensus development meetings for novel ideas.*^{159,184} *The HTA monograph describes that during the open meeting a presentation should be made by a presenter who is not part of the closed meeting. We preferred not to adopt this approach for a number of reasons:*

- Asking panel members to deliver a presentation ensured they were familiar with the latest relevant literature relating to the closed meeting questions.*
- Delegates of the open meeting would be most interested in hearing presentations from panel members, as they were recognised experts in the field.*
- From a practical point of view we were able to support the travel costs for panel members to attend the consensus meeting by ensuring panel members were presenting faculty at the open meeting.*

*A similar approach of using panel members as open meeting speakers was adopted in the Doha Agreement on Groin Pain in Athletes.*¹⁸⁴ *The groin pain consensus meeting ensured that there were up to date systematic reviews conducted in each topic area. Panel members prepared these in advance. Unfortunately, I was not able to do this within the time constraints of setting up our meeting. We did circulate reading material, which included recent systematic reviews where available. Panel members were also able to suggest additional material when they felt we had made an omission. We made these efforts to ensure all panel members were familiar with the latest literature and could discuss this if required during the closed meeting. We also chose to include a measure of the panel's level of agreement. This has been used in the development of the EULAR guidelines.*¹⁵⁹ *Quoting the level of agreement in the manuscript was useful as it provided additional weight to the outcomes, while allowing members who held disparate views to voice them without feeling they weren't being heard.*

Were I to repeat the process again I would like to see more opportunity for discussion at the open meeting. Delegates were informed at the time we were planning a consensus statement and they were enthusiastic to share their views. I also wish that I had minuted or recorded those discussions and had been able to refer back to them in the closed meeting. With more planning time I would have conducted formal literature reviews relating to each topic.

This consensus development conference provided me many opportunities to develop and learn as a researcher. This entire event took considerable effort to organise. DG focused on organising the open meeting, while I focused on organising the closed consensus development conference. I was able to observe what was required in organising a large open meeting; from inviting speakers, sponsors and delegates to choosing appropriate topics, presentation titles and planning the programme. The format of the Sports Hip meeting is to facilitate audience participation rather than numerous didactic lectures. The biggest challenge I observed in organising the meeting was restricting the size of the programme in order that there was sufficient time for discussion of each topic.

In arranging the closed consensus development conference I was able to make new contacts and network with people who I might not otherwise have met. I was pleased that I was able to chair the event. Originally we had considered a more established figure to chair the meeting. We were concerned that as a junior researcher I might not command the authority from the consensus panel. Our original chairperson was the head of the International Olympic Committees medical team and to my benefit, he had to go to the Rio Olympics early due to the Zika virus outbreak. I was happy with my performance as a chairman and received positive feedback. I believe I met the challenges in maintaining progress through the agenda, reigning in members with strong opinions and much to say, while including the quieter members of the group in the discussion. Overall it was a great opportunity and experience for me.

In summary this chapter has allowed me to explore and understand consensus development techniques. I was able to use these to achieve my objectives of defining FAI syndrome and how it should be diagnosed. The consensus development conference gave me a unique opportunity to chair an international multidisciplinary meeting of senior academics and clinicians. The meeting also provided a chance to network and make contacts in my field of research. Despite the success of the consensus meeting there are areas that require further research; particularly defining cam and pincer morphology.

4 Developing criteria to define cam and pincer morphology

In this chapter I compare the imaging findings of patients with FAI syndrome and matched controls in order to establish what diagnostic criteria should be used to define the presence of cam and pincer morphology for epidemiological research.

Declarations

I received the following help in writing this chapter:

D Griffin; helped design method to assess pincer morphology.

L Laver; assessed the reliability of measurements by assessing the inter-observer reliability.

This work has been presented at a national conference:

Title: Definition and Epidemiology of FAI Syndrome. Presenter: E Dickenson.

Event: Sports Hip Meeting, June 2016.

This work has been submitted for publication:

Dickenson E, Ahmed , Laver L, Wall, P, Hutchinson C, Griffin D. A 3-Dimensional measure of acetabular morphology: Subtended edge angle.

This study was sponsored by University Hospitals Coventry and Warwickshire.

NHS Research and Development approval was obtained for this study.

4.1 Introduction

In chapter 2 I described how the prevalence of cam and pincer morphology in the general population remains unknown. This was partly due to the wide variety of methods used to define cam and pincer morphology. There seemed little scientific justification behind the selection of the criteria used in the various studies. In chapter 3 a consensus panel agreed that in order to diagnose FAI syndrome cam or pincer morphology must be identified on diagnostic imaging, in addition to the presence of appropriate symptoms and clinical signs. However the panel were unable to agree how cam or pincer morphology should be objectively measured, due in part to a lack of evidence supporting any one method. Only one study has previously attempted to assess the sensitivity and specificity of α angles in determining the presence of cam morphology.¹⁵⁸ However there were significant sources of bias in the assessments made in this study and further verification studies are required.

Prior to attempting to measure the point prevalence of cam and pincer morphology in the population, I need to develop rationale criteria to establish their presence and understand the diagnostic accuracy of those criteria.

In chapter 3 the consensus panel agreed that cam and pincer morphology are best assessed using cross sectional imaging. They stated that using plain radiographs alone were only moderately sensitive. This finding is supported by the work of Rhakra et al.¹³⁸

In this chapter I will separately attempt to define the accuracy of measures of cam and pincer morphology. I will present the methods and results as distinct sub chapters (4.2 for cam and 4.3 for pincer morphology), as there are unique issues with defining each, although there is overlap in the methodology I use.

I intend to determine the optimal measures of cam and pincer morphology in order that they can be used to determine the point prevalence of the respective hip shapes in the population. In order to assess the diagnostic accuracy of both

measures of cam and pincer morphology I shall use a case control (multi-gated) diagnostic accuracy study and attempt to report the study in line with the STARD guidelines.^{189,190}

4.2 Cam Morphology

In determining how to measure the presence of cam morphology, various members of the consensus panel in chapter 3 proposed different thresholds for α angles. In chapter 2 α angles were also the most widely used measure of cam morphology.¹⁴⁸ α angles are a widely used, reproducible and valid measure of cam morphology, they also allow assessment in three-dimensions by assessing at different points around the axis of the femoral neck.⁶² I therefore chose to assess the diagnostic accuracy of α angles to determine the presence of cam morphology. I intend to identify the optimum imaging plane and threshold value that will distinguish subjects with cam morphology (defined by subjects with cam type FAI syndrome) and the general population.

4.2.1 Objectives:

- To identify the optimal measure in order to distinguish cam morphology in patients diagnosed with FAI syndrome, from the general population, and define the measures diagnostic utility.

4.2.2 Methods

In this study I use a retrospective multi-gated diagnostic accuracy study (also referred to as case control diagnostic study) to identify cases diagnosed with cam type FAI syndrome and compare their hip shapes to non-diseased subjects.¹⁸⁹ NHS Research and Development approval was obtained for this study.

Cases (gate one):

UK surgeons participating in the FASHIoN trial identified case hips from patients seen in their hospitals' out patient clinic.⁸⁰ The FASHIoN study is a multicentre

randomised controlled trial of arthroscopic surgery versus conservative care for patients with FAI syndrome. Surgeons with a high volume adult hip arthroscopy practice were invited to participate in the trial. When patients were recruited into the trial, surgeons stipulated whether the patient had cam, pincer or mixed type FAI syndrome. As part of establishing the diagnosis, surgeons performed cross sectional imaging; either CT or MR. In order to maintain consistency with the imaging of controls, only cases with CT imaging were considered.

A random sampling method was adapted when there were more cases available in the sample population than required to meet the sample size. This was stratified to ensure there was representation of all surgeon and all centres in the sample.

The UK FASHIoN study is of a pragmatic design, meaning its results are intended to be generalisable to patients treated for FAI syndrome across the NHS. It does however have its own eligibility criteria. These are:

Inclusion criteria:

- Age ≥ 16 (no upper age limit);
- Symptoms of hip pain - patients may also have symptoms of clicking, catching or giving way;
- Radiographic evidence of pincer- and/or cam-type FAI morphology on plain radiographs and cross-sectional imaging, defined as:
 - Cam morphology - an alpha angle $>55^\circ$ ⁶²
 - Pincer morphology - a lateral centre edge angle of $>40^\circ$ or a crossover sign on the antero-posterior radiograph of the pelvis ⁶¹
- The treating surgeon believes the patient would benefit from arthroscopic FAI surgery;
- The patient is able to give written informed consent and to participate fully in the interventions and follow-up procedures.

Exclusion criteria

- Evidence of pre-existing osteoarthritis, defined as Tonnis grade >1 , ³⁹ or more than 2mm loss of superior joint space width on antero-posterior pelvic radiograph;⁶⁹

- Previous significant hip pathology such as Perthes' disease, slipped upper femoral epiphysis, or avascular necrosis;
- Previous hip injury such as acetabular fracture, hip dislocation or femoral neck fracture;
- Previous shape changing surgery (open or arthroscopic) in the hip being considered for treatment.

By using subjects identified as having cam type FAI syndrome (symptoms, clinical signs and imaging findings) as the reference standard I hope to assess the suitability of the measures of cam morphology, my index test.

Controls (gate two):

Subjects who presented following major trauma to University Hospitals of Coventry and Warwickshire (UHCW) in 2015 were identified. Those who had undergone a major trauma CT scan (which included the pelvis) were potential controls. Potential controls were excluded if they died, had pelvic, acetabular or proximal femoral fractures. Controls were identified from this group by randomly selecting subjects who were age and sex-matched to the case hips. Potential controls electronic medical records were screened to ensure they had not been diagnosed or treated for FAI syndrome. The morphology of both hips in control subjects was analysed, compared to just the affected hip in case subjects, creating 2:1 matching of controls to case hips.

Imaging Analysis:

Images were analysed using OsiriX digital imaging and communications in medicine (DICOM) viewer (Geneva, Switzerland) version 8.0.1.¹⁹¹

Proximal femoral morphology was assessed by measuring α angles around the femoral neck at 30° intervals corresponding to hour increments on a clock face.⁶² The 12 o'clock position was defined as the most cranial aspect of the femoral head neck junction, relative to the long axis of the femur and the 3 o'clock position corresponded to the anterior femoral head neck junction. For each hip,

12 α angle measurements were made using multi-planar reconstructions around the axis of the femoral neck. The α angle was defined as the angle between the axis of centre of the femoral neck, the centre of the femoral head and the point at which the bony contour of the head neck junction exceeded the radius of the head, see Figure 7. Cam morphology may be present across the antero-superior head neck junction (12-3 o'clock), therefore a mean of α angles measured at 12, 1, 2 and 3 o'clock was determined.¹³⁸

In order to assess the intra-observer reliability of the test, repeat measurements were made on 20 randomly selected subjects at least 1 month after the initial measurement. Lior Laver, an Israeli orthopaedic surgeon working as DG's fellow from February 2017 to August 2017, made repeat measurements in order to determine the inter-observer reliability.

The femoral neck shaft angle was measured on coronal maximum intensity projection reconstructions of the CT (providing a view similar to an AP radiograph).³⁹ When corresponding axial slices of the femoral condyles were available femoral neck antetorsion was measured.^{46,192}

Statistical analysis

Summary statistics were used to describe each measure for cases and controls. The inter- and intra-observer reliability of α angles was calculated by assessing the inter class correlation coefficient for absolute agreement. The α angles at each position around the axis of the femoral neck were reported for cases and controls and means values were compared with an independent students t-test. The receiver operator characteristics (ROC) of measures that reached statistical significance ($p < 0.05$) were plotted to determine which measure best-defined cam morphology.

The measure with the greatest area under the receiver operator curve (AUC) was used to determine the optimal measure. With an AUC of 0.5 the measures ability to detect disease is equivalent to chance alone. An AUC of 1.0 would be a perfect

discriminatory measure. Threshold values were determined by calculating the value with the greatest Youdon's index.¹⁹³ The Youdon's index is a method to determine the optimal sensitivity and specificity of a given measure. It is determined by identifying the point on the ROC curve that reaches the greatest vertical distance from the diagonal constant. This provides a mathematically reasoned optimal threshold, assuming that sensitivity and specificity are of equal importance in the diagnostic test. It can also be calculated by identifying the threshold value that has the greatest sum of the sensitivity and specificity. Contingency tables were produced for the optimal threshold.

Sample Size Calculation

A sample size calculation was performed to determine the number of subjects required to establish a given 95% confidence interval width for a ROC curve.^{194,195}

Table 11 provides different scenarios in terms of numbers of cases required for an anticipated sensitivity and specificity for different confidence interval widths. I chose to use an anticipated sensitivity and specificity of 80% and 70% respectively, with a 95% confidence interval width of 0.15. Using these parameters the number of cases required was 60. Allowing for a 2:1 ratio of control to case hips the required sample size was 180 hips.

Table 11 Sample Size Calculation for determining the confidence interval width of a ROC given an anticipated false positive and true positive rate for a case to control ratio of 1:2. Table adapted from Machin 2011 ¹⁹⁵

False positive rate (1- specificity)	True positive rate (sensitivity)	Width of 95% confidence interval for area under curve.		
		0.1	0.15	0.2
0.2	0.7	134	60	34
	0.8	103	46	26
	0.9	60	27	15
0.3	0.7	160	71	40
	0.8	134	60	34
	0.9	90	40	23

4.2.3 Results

Sampling

A flow diagram for the selection of subjects that were analysed is displayed in Figure 10, the demographics of these cases is shown in Table 12. In total 351 patients were randomised in UK FASHIoN, of which 121 had undergone a CT scan. Cam type FAI syndrome cases were available for analysis from 12/24 sites (16 surgeons).

Figure 10 Selection of cam cases to be analysed

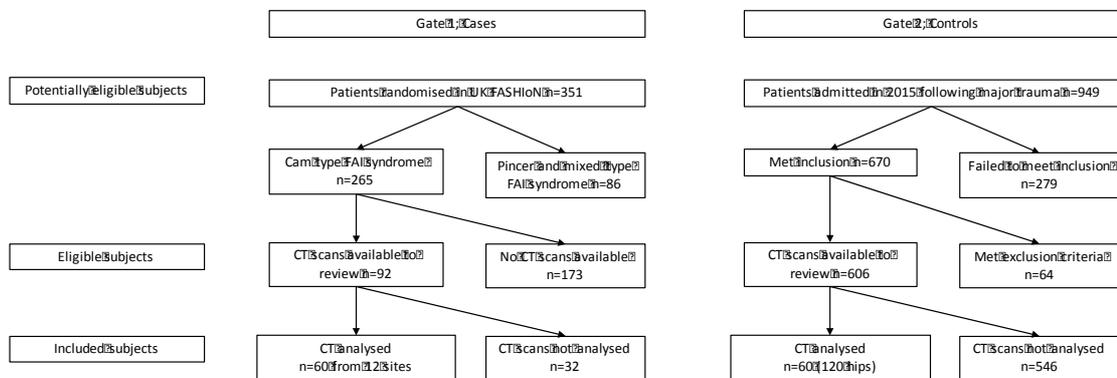


Table 12 Demographics of Cases

	Cam cases	Controls
n	60	60 subjects (120 hips)
Mean age (SD)	33 (SD 8.7)	33 (8.7)
Sex	44male 16female	44male 16female

Image analysis

The inter- and intra-observer reliability of measuring α angles was 0.873 (95%CI 0.85-90) and 0.903 (95%CI 0.87-0.93) respectively. The standard error of the measurement was 3.4°. Histograms showing the distribution of alpha angle measurements in the antero-superior head neck junction are displayed in Figure 11.

The mean α angles around the femoral head neck junction for cases and controls is displayed in Table 13. The mean α angle was higher, reaching statistical

significance in the case group compared to controls at 11, 12, 1, 2, 3, 4 and 7 o'clock. A visual representation of the differences in α angle around the femoral neck for all case and control hips are displayed in the radar plots in Figure 12, the mean values displayed in Figure 13. Radar plots for individual cases and controls are displayed in the Appendix.

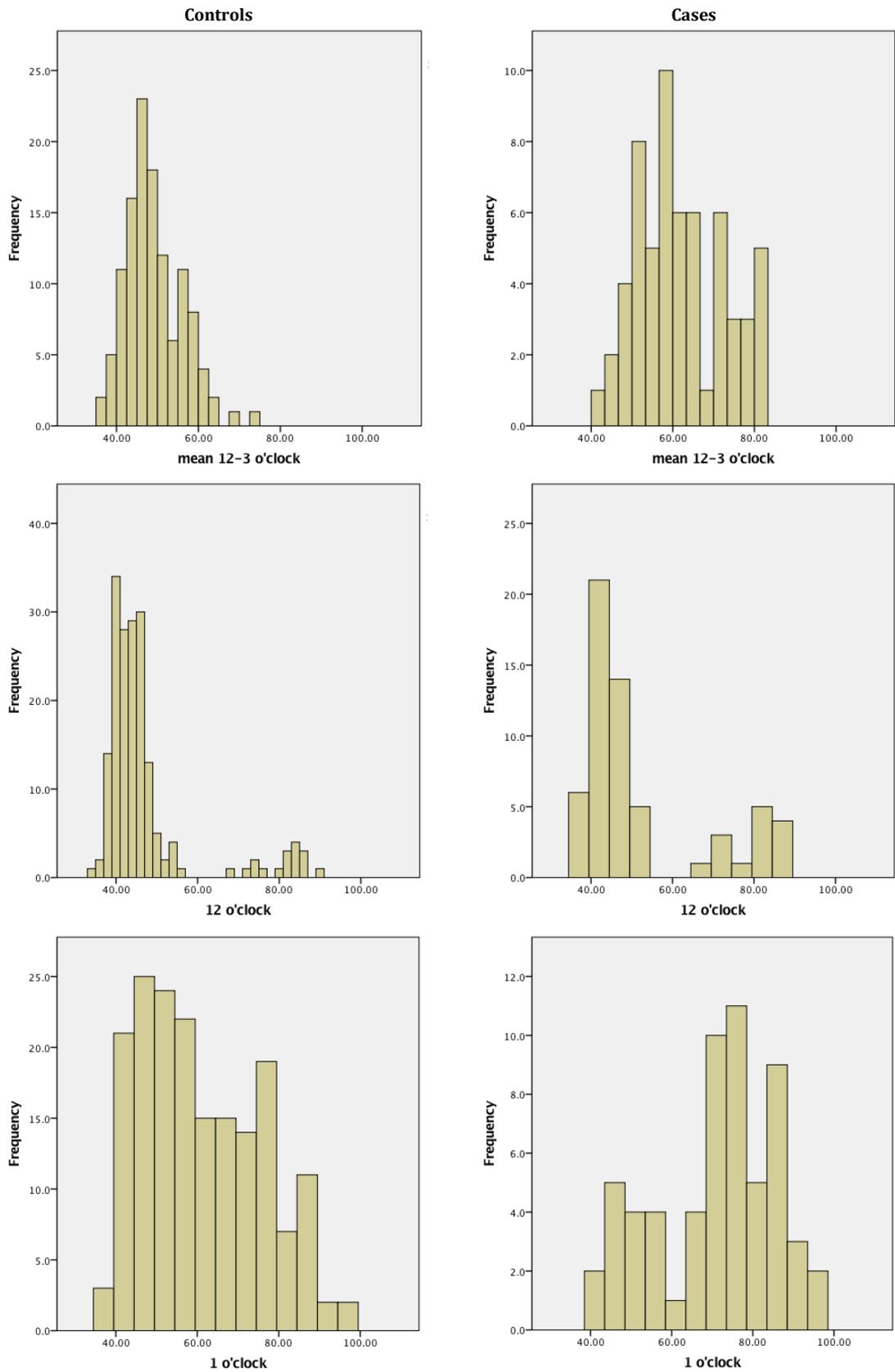
The mean femoral neck shaft angle for cases was 132° (SD4.3) and 132° (SD 3.8) for controls [p=0.954].

Fifty-three cases had axial cuts of the knees that allowed assessment of femoral neck antetorsion; no controls had axial cuts of knees (normal CT trauma protocol does not image below lesser trochanter). The mean femoral neck antetorsion for case hips was 14.4° (SD7.2).

Table 13 Mean alpha angle around the femoral neck for cases and controls

Position on femoral neck; o'clock	Mean α angles/ $^{\circ}$ (SD)												Mean of α angles between 12 and 3
	12	1	2	3	4	5	6	7	8	9	10	11	
Cases	53 (16.1)	71 (14.8)	68 (12.1)	56 (13.5)	41 (7.2)	40 (4.1)	43 (3.6)	41 (3.0)	37 (3.3)	39 (3.8)	44 (6.1)	44 (11.1)	62 (10.6)
Controls	43 (7.2)	56 (12.2)	53 (10.6)	43 (7.9)	36 (4.1)	39 (4.7)	42 (3.1)	40 (3.3)	37 (3.2)	39 (3.9)	43 (5.1)	41 (3.7)	49 (6.8)
p=	<0.001	<0.001	<0.001	<0.001	<0.001	0.136	0.124	0.030	0.948	0.176	0.326	0.002	<0.001

Figure 11 Histograms of alpha angles measured at 12, 1, 2 and 3 o'clock and the mean of alpha angles measured between 12 and 3 o'clock, for cases and controls.



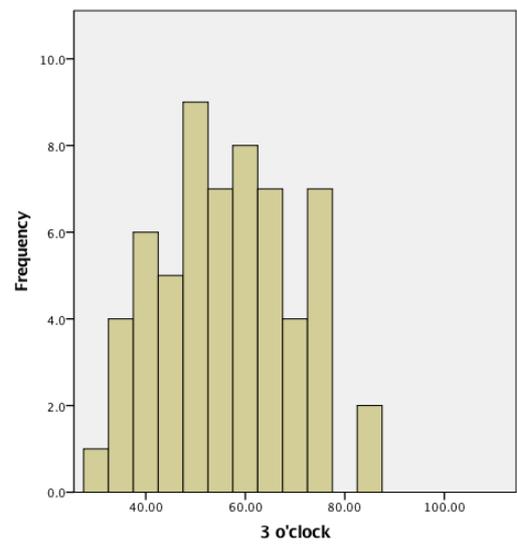
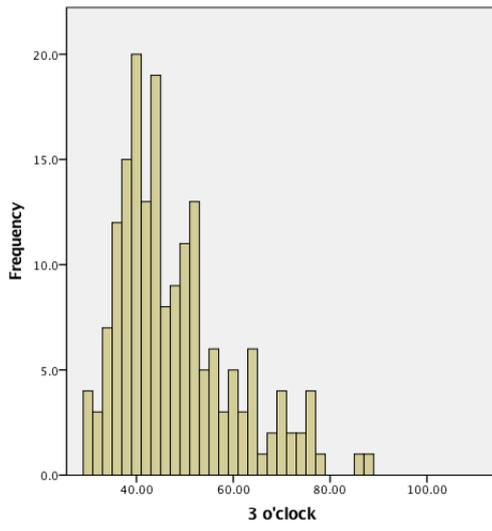
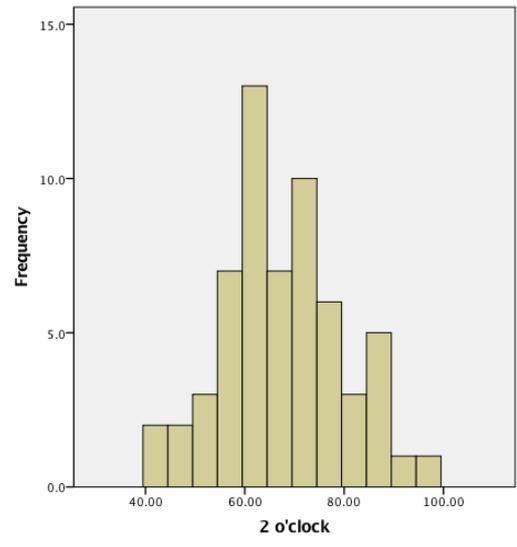
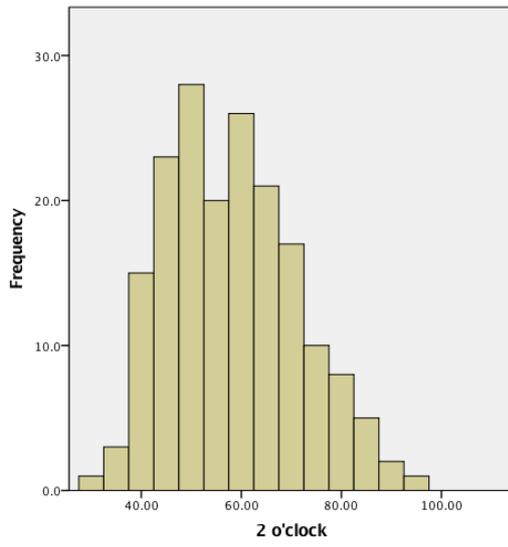
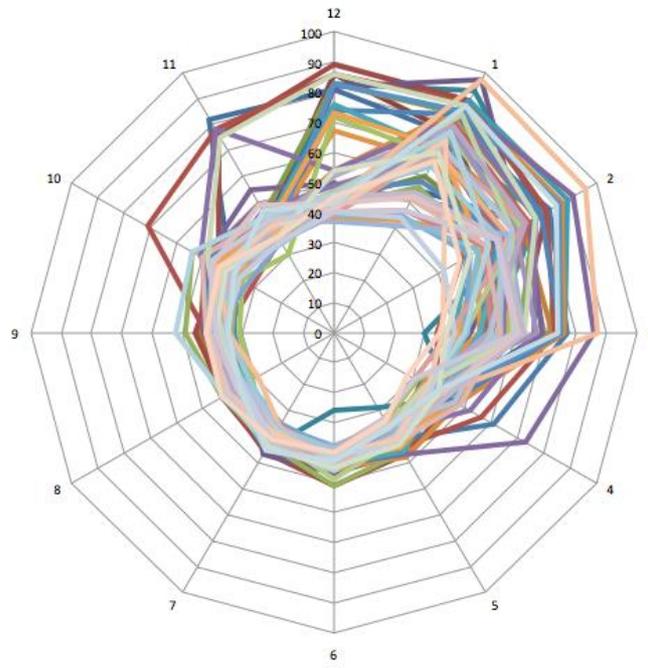


Figure 12 Radar plots of all cam morphology case and control hips showing alpha angles measured around the femoral head neck junction

Case Hips



Control Hips

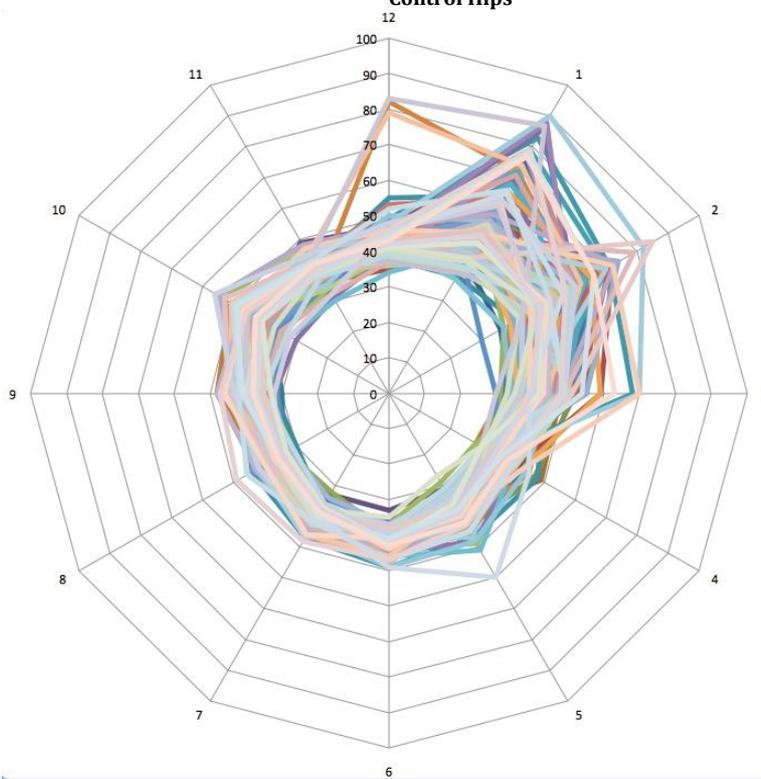
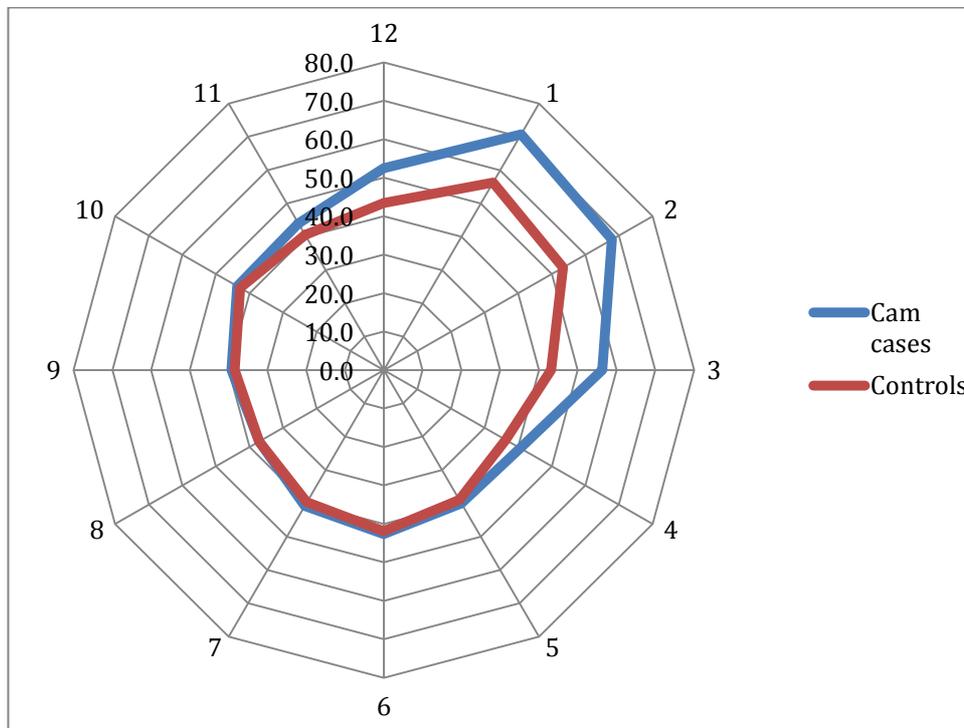


Figure 13 Radar plot of alpha angles around the femoral head neck junction, showing mean values for cases and controls



Receiver Operator Characteristics

The ROC curves for α angles were plotted for each of the positions on the femoral head neck junction where there was a statistically significant difference between cases and controls. The resulting ROC tables with AUC are shown Table 14. For measures where the 95% confidence interval did not cross 0.5 the resulting ROC curve is displayed in Figure 14. Individual ROC curves are displayed in Figure 15 to Figure 21. The tables displaying the values for the coordinates of the ROC curve are available in the appendix.

The mean of α angles measured between 12 and 3 o'clock had the best performing receiver operator characteristics with an AUC of 0.85 (95% CI: 0.79, 0.91).

Table 14 Summary of ROC area under curve

Area Under the Curve					
Test Result Variable(s)	Area	Std. Error ^a	Asymptotic Sig. ^b	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
12 o'clock	0.681	0.043	0.000	0.597	0.765
1 o'clock	0.766	0.040	0.000	0.688	0.844
2 o'clock	0.817	0.033	0.000	0.753	0.882
3 o'clock	0.793	0.039	0.000	0.717	0.870
4 o'clock	0.713	0.041	0.000	0.632	0.794
11 o'clock	0.551	0.048	0.269	0.457	0.644
7 o'clock	0.603	0.044	0.025	0.517	0.688
Mean of alpha angles from 12 to 3 o'clock	0.851	0.030	0.000	0.792	0.910
a. Under the nonparametric assumption					
b. Null hypothesis: true area = 0.5					

Figure 14 ROC curves for the α angles measured at different positions on femoral head neck junction in cam type FAI syndrome

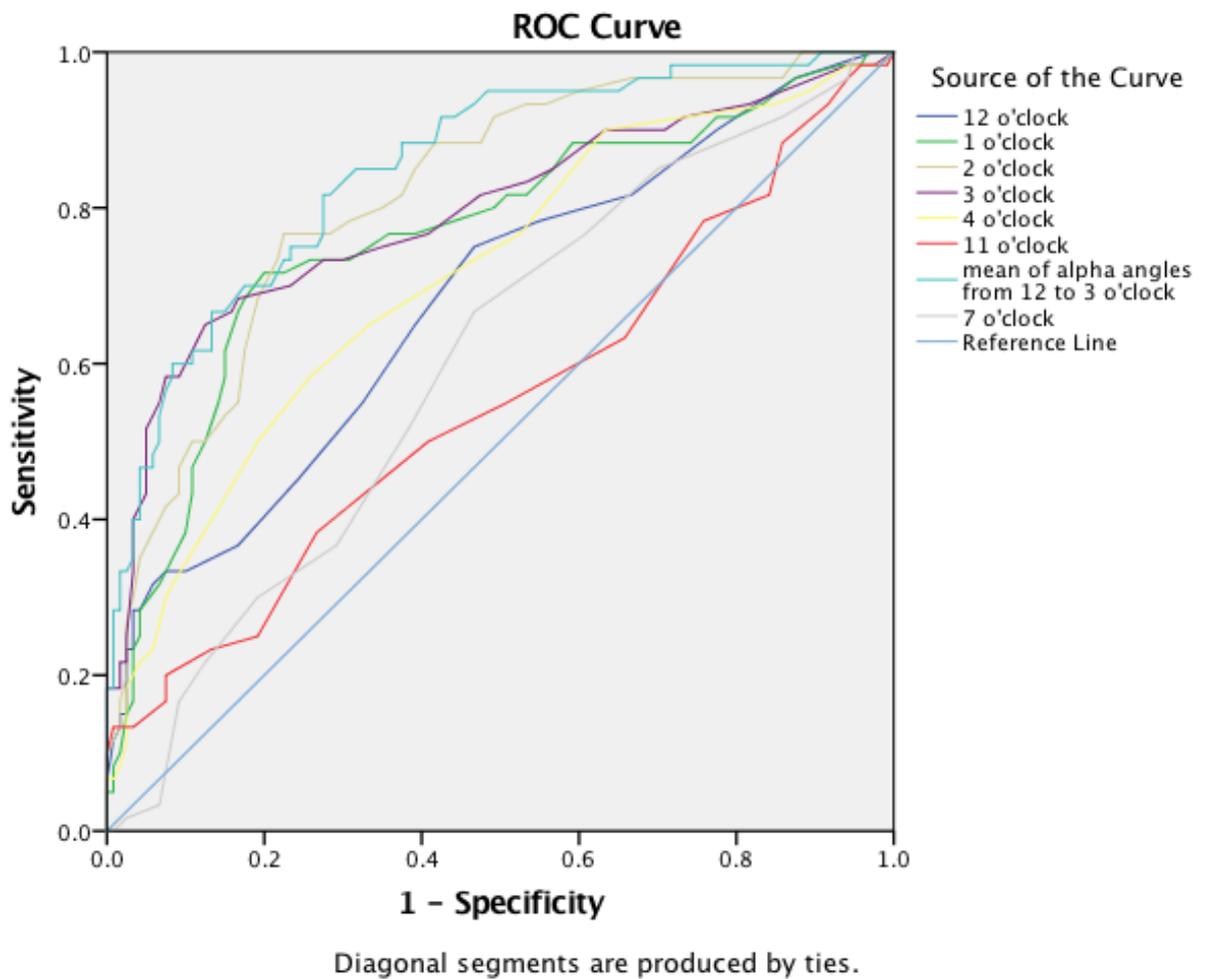


Figure 15 ROC curves for the mean of α angles measured between 12-3 o'clock- the measure with the greatest AUC.

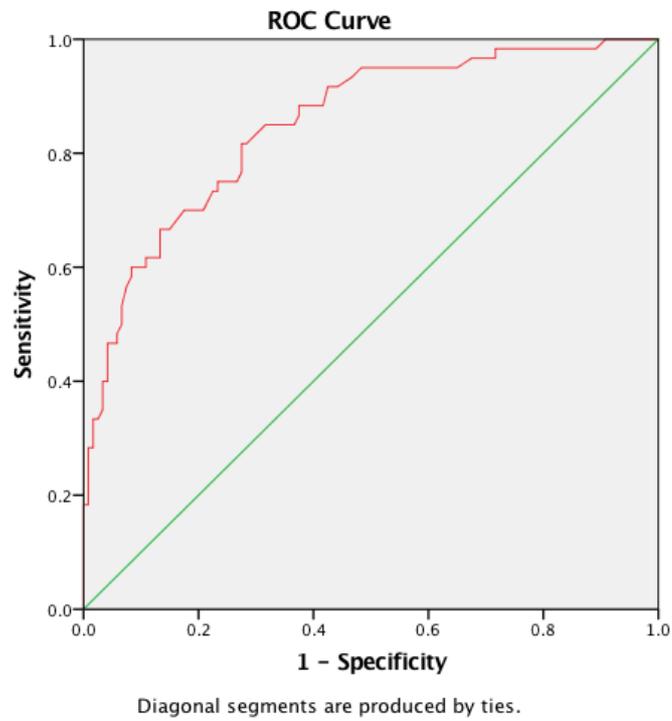


Figure 16 ROC curves for the α angles measured at 12 o'clock

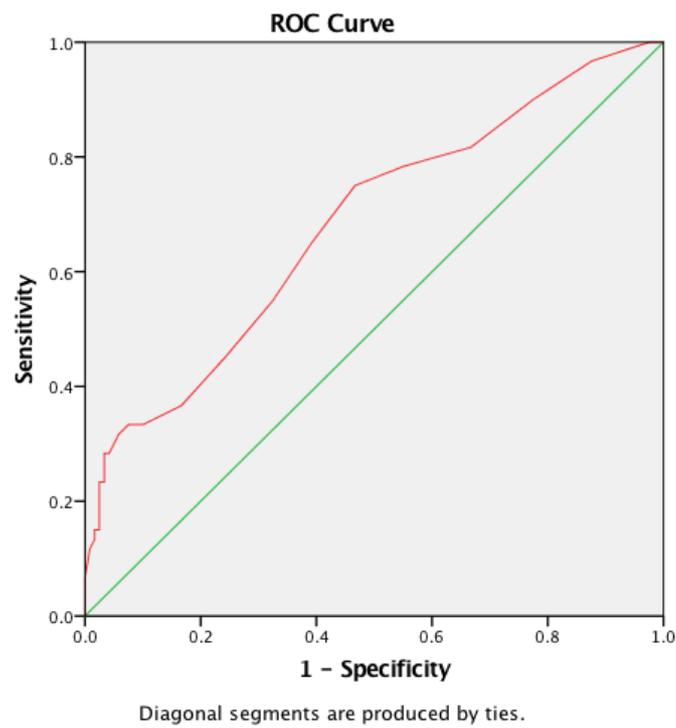


Figure 17 ROC curves for the α angles measured at 1 o'clock

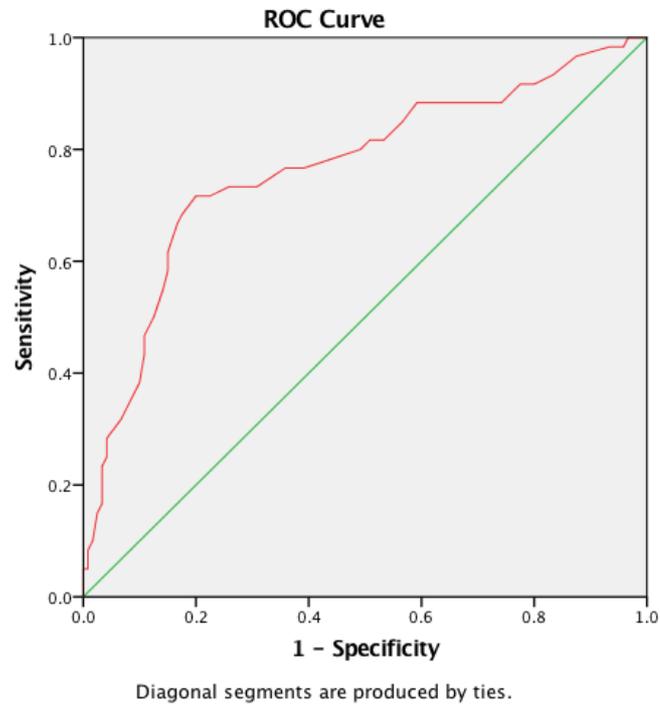


Figure 18 ROC curves for the α angles measured at 2 o'clock

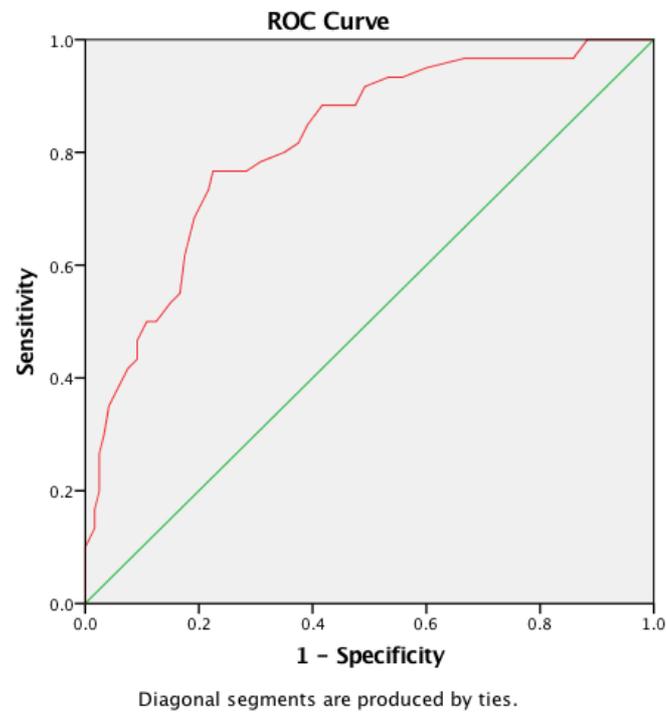


Figure 19 ROC curves for the α angles measured at 3 o'clock

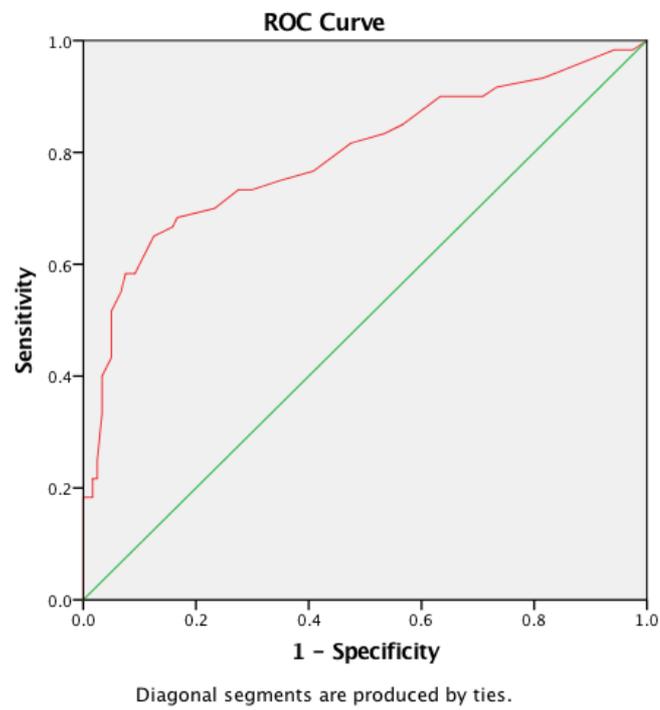


Figure 20 ROC curves for the α angles measured at 4 o'clock

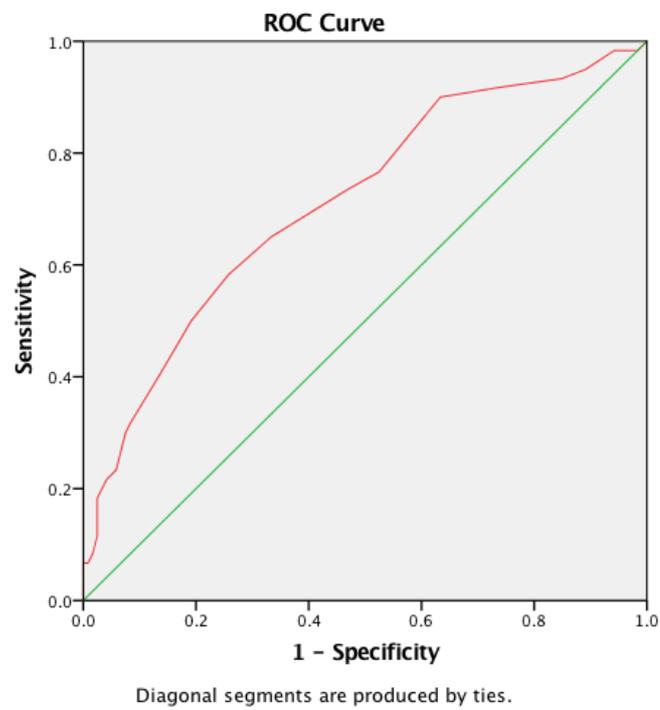
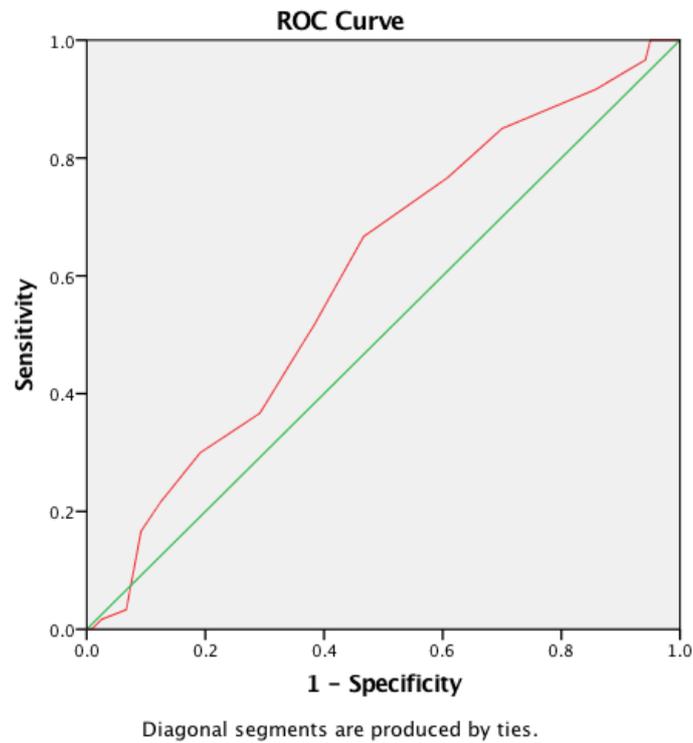


Figure 21 ROC curves for the α angles measured at 7 o'clock



Youden's Index Cam Morphology

The optimal threshold for the mean of α angles measured between 12 and 3 o'clock was 52.2° . This yielded a sensitivity of 82% and a specificity of 73%.

Contingency Tables

Table 15 Contingency Tables for determining the presence of cam morphology using the mean of α angles between 12-3 o'clock greater than 52°

Mean of α angles measured between 12-3 o'clock $>52^\circ$	FAI syndrome		Sum
	+	-	
+	49	33	82
-	11	87	98
Sum	60	120	180
Sensitivity = 82% Specificity = 72% Positive predictive value = 60% Negative predictive value = 89%			

4.3 Pincer Morphology

The present measures of pincer morphology are largely made on plain AP radiographs. The use of plain radiographs requires the x-ray to be appropriately centred without excessive rotation or pelvic tilt.^{172,173} When x-rays are inadequately centred, tilted or rotated, this adds an additional complexity in interpreting the images. The consensus panel stated that measures made on plain radiographs are likely to be only moderately sensitive and preferred measures made on cross sectional imaging. In chapter 2 I identified two measures of pincer morphology that relied on cross sectional imaging; acetabular anteversion and acetabular depth.^{16,39} However these measures both used a single slice of a cross sectional scan to make an assessment. Therefore, they were not making a true assessment of the three-dimensional shape of the acetabulum.

When considering the presence of pincer morphology the consensus panel stated that it was important to assess the depth, orientation and the rim of the acetabulum. At present no single measure is capable of assessing these factors. In the introduction I describe a pre existing measure that assesses rim morphology and depth (see Figure 1), which was developed to consider acetabular cup position in hip arthroplasty.¹³ In this study, focused on defining pincer morphology, I describe the development and testing of this measure to assess acetabular morphology in three dimensions and the assessment of its diagnostic accuracy, making comparisons to conventional methods.

4.3.1 Objectives:

- To develop and test a cross sectional imaging measure of acetabular morphology, which assesses depth, orientation and rim morphology, in order to determine the presence of pincer morphology.
- To identify the optimal measure in order to distinguish pincer morphology in patients diagnosed with FAI syndrome, from the general population and to define the measure's diagnostic utility.

4.3.2 Methods

Cases (gate 1)

The same methods as used previously for cam morphology were applied to identify cases of pincer morphology from the UK FASHIoN study (see 4.2.2).

By using subjects identified as having pincer and mixed type FAI syndrome (symptoms, clinical signs and imaging findings) as the reference standard I intended to assess the suitability of the measures of pincer morphology, i.e. my index test.

Controls (gate 2)

The same method was used to identify pincer controls as was used in the assessment of cam morphology (see 4.2.2)

Imaging Analysis

Acetabular Subtended Edge Angles

Following discussion with my supervisor (DG) I decided to evaluate a measure that would assess the acetabulum in three-dimensions. He called this measure the '*acetabular subtended edge angle*' (SEA) and presented the technique at the ABJS Carl T Brighton Workshop on Hip Preservation Surgery convened by Klaus Siebenrock and Chris Peters in 2011.¹⁹⁶ This particular technique has never been published but is similar to the SEA technique that was developed and published by Vandebussche and more recently Cobb.^{13,14}

The SEA measures acetabular morphology on cross sectional imaging but in a standardised reference plane. The measure corrects for pelvic tilt, rotation and obliquity by re-orientating imaging to the anterior pelvic plane.¹⁹⁷ The anterior pelvic plane is the anatomical plane that exists between the right and left anterior superior iliac spines and right and left pubic tubercles; see Figure 22. Once images are referenced to the anterior pelvic plane they are re-orientated to a standardised *acetabular axis* (see below), this is intended to reflect the *normal* orientation of the acetabulum.¹⁹⁸ The acetabular axis is an imaginary line that passes through the

centre of the acetabulum, at 45° abduction and with 15° anteversion relative to the anterior pelvic plane; see Figure 23.

Figure 22 Anterior Pelvic Plane

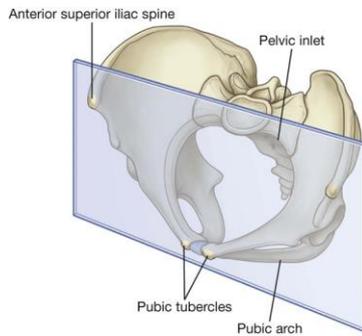


Figure 23 Direct lateral view of pelvis. The blue points represent the ASIS and pubic tubercle, defining the anterior pelvic plane. The line represent the acetabular axis.



In order to measure the SEA the following steps were followed:

1. CT DICOM files are opened in the multi-planar reconstruction (MPR) view offering axial, coronal and sagittal views.
2. The plane of the MPR is orientated to the anterior pelvic plane, see Figure 24.
3. The centre of acetabular rotation is identified, by identifying the centre of the femoral head. The MPR is centred on this point in all three axes. Images are

reoriented to align to the acetabular axis which is 45° of abduction in coronal plane (see Figure 25) and then 15° of anteversion in axial oblique plane (see Figure 26).

- SEAs are measured around the acetabular axis. SEAs measure the angle between the acetabular axis, the centre of the femoral head and the rim of the acetabulum (see Figure 27)
- 12 SEA measurements are made around the acetabular axis with 12 o'clock representing the most cranial point, and 3 o'clock representing the most anterior point on the acetabulum (see Figure 28). The initial coronal oblique view represents 12 and 6 o'clock and the axial oblique view represents 3 and 9 o'clock.
- Measurements are made at the remaining points around this axis by rotating 30° radially around acetabular axis (the sagittal oblique). In a right hip rotating 30° anticlockwise will move the points displayed from 12 to 11 o'clock and 3 to 2 o'clock. In the left hip rotating 30° clockwise is necessary to change to view these points. This step is repeated once so 12 measures are made.

Figure 24 CT Multi-planar reconstruction orientated to anterior pelvic plane

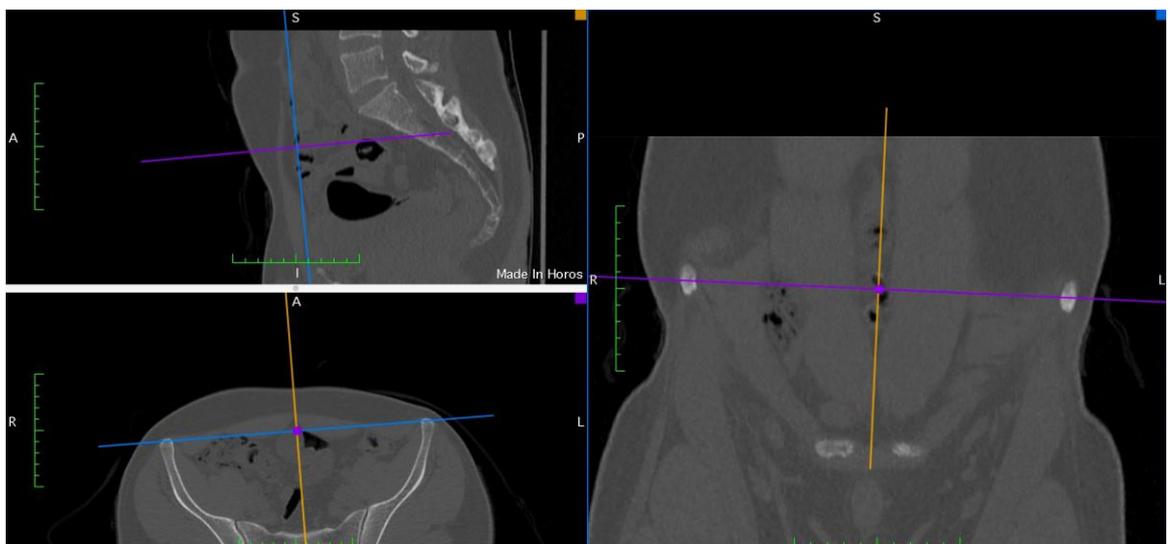


Figure 25 CT in anterior pelvic plane centred on middle of femoral head, and then rotated around the coronal axis 45° (see right hand image).

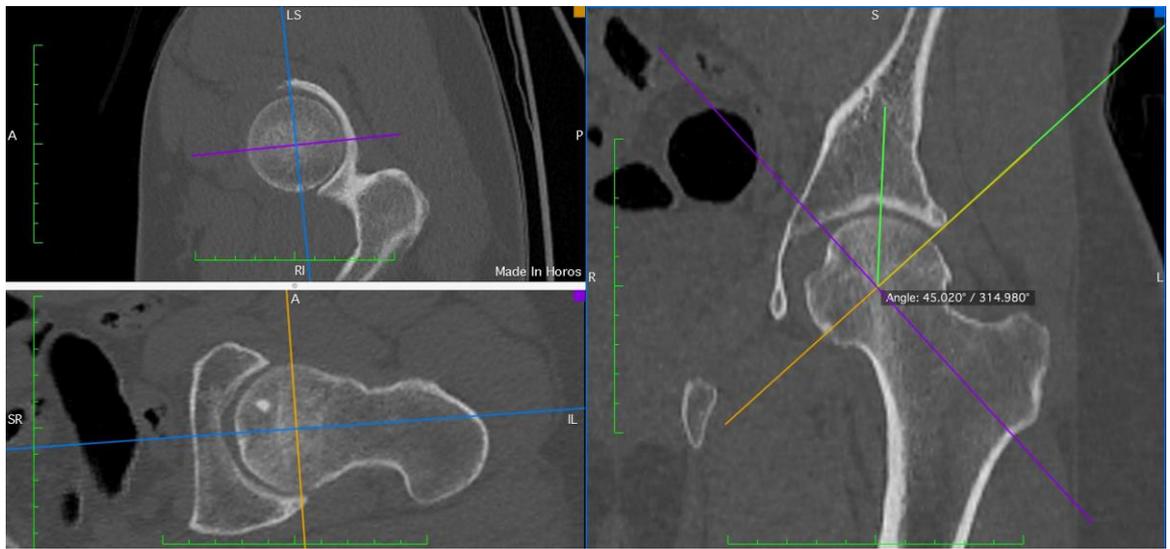


Figure 26 Following 45° abduction in coronal plane (right hand image), the 15° anteversion has been measured (bottom left image) and applied to create the *acetabular axis*.



Figure 27 SEA are measured between the acetabular axis (line 1), the centre of the femoral head and the rim of the acetabulum (line 2). This position corresponds to 3 o'clock. The SEA is 68 degrees.

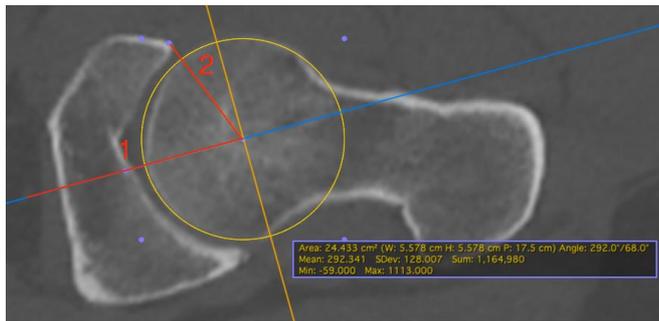


Figure 28 Once the SEA have been measured at all available positions; right hand image 12 o'clock superiorly and 6 o'clock inferiorly, bottom left 3 o'clock at top and 9 o'clock at bottom, the image plane is rotated 30° on the sagittal oblique (top left) in order to measure the remaining positions around acetabular axis. Rotating 30° clockwise for a left hip (anti clockwise for right hip) on the sagittal oblique will then show the 11 o'clock position on the acetabular rim at the top of the right hand image and the 2 o'clock position on the acetabular rim at the top of the bottom left image.

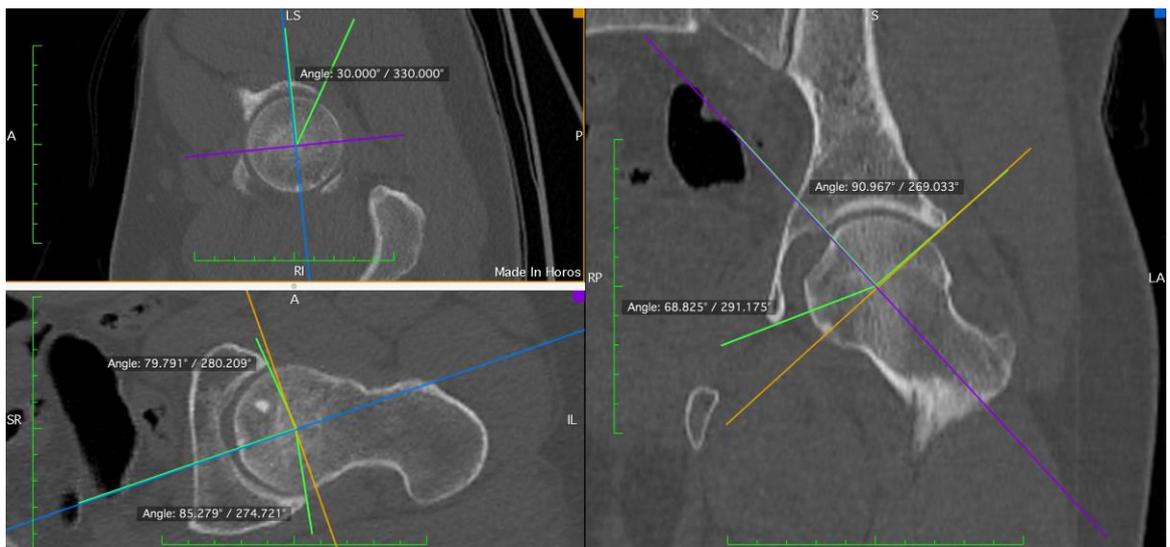
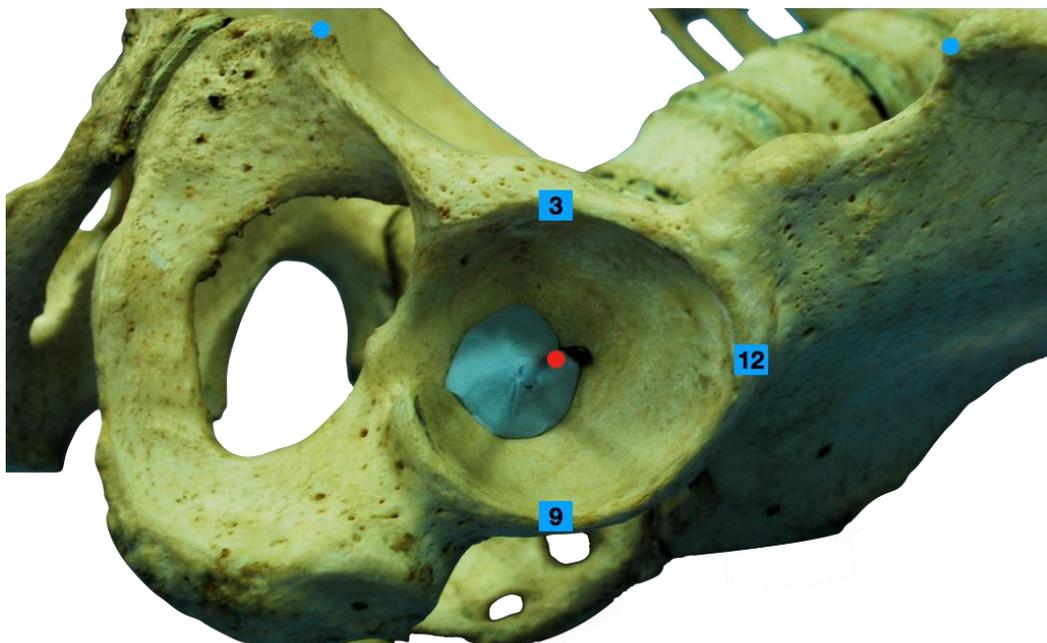


Figure 29 Following 30° clockwise rotation around acetabular axis SEAs are measured at 11 and 5 o'clock (right hand image) and 8 and 2 o'clock (bottom right). To complete the 12 measurements a further 30° clockwise rotation around acetabular axis (top left) is required.



Figure 30 View of the acetabulum along the acetabular axis (red dot). The blue dots represent the ASIS and pubic tubercle. The 3, 12 and 9 o'clock positions are identified.



To assess pincer morphology I will measure the SEAs around the acetabular axis. The SEA was intended to assess the three factors important in the assessment of pincer morphology described in chapter 3; depth, orientation and rim morphology. The individual measures of SEA around the acetabular axis are an indication of the

rim morphology, with a higher value indicative of a prominent rim in that position. In order to assess orientation and depth additional analysis is required. To assess the depth the sum of the SEAs around the acetabular axis, excluding the SEA assessing the cotyloid fossa (5, 6 and 7 o'clock), will be determined; this will be called the *SEA depth*. To assess orientation (or anteversion) a ratio of the posterior SEAs (8, 9, 10 and 11 o'clock) to the anterior SEAs (1, 2, 3 and 4 o'clock) will be determined. This will be called the *SEA anteversion*. A lower ratio of SEA anteversion will indicate an acetabulum less anteverted, a higher ratio will suggest more anteversion. A ratio of 1, will indicate the acetabulum is anteverted 15° (note step 4 and Figure 26 in measuring the SEA) if all other factors are equal.

In order to assess the intra-observer reliability repeat measurements were made on 20 randomly selected subjects at least 1 month after the initial measurements were made. LL also made repeat measurements in order to determine the inter-observer reliability.

To further assess pincer morphology, and to serve as a comparator to SEA, I assessed conventional measures of pincer morphology. These included the CEA, acetabular anteversion and acetabular depth. I chose to also assess these measures as they independently assess the depth, orientation and rim of the acetabulum. The CEA is traditionally determined from a plain radiograph and is measured by the intersection of a vertical line from the centre of the femoral head and a line from the centre of the femoral head to the superiolateral edge of the acetabulum.⁶⁷ CEAs were measured on a maximum intensity projection of the CT in the coronal plane. Acetabular anteversion was measured using the technique described by Dandachli's; see appendix.¹⁹⁹ A coronal slice giving adequate visualisation of the acetabular roof and pelvic tear-drop was used to divide the acetabulum into quarters between these 2 landmarks. Acetabular version was measured on axial cuts at the boundary between the superior and middle quarters. Acetabular depth was measured according to the technique described by Pfirrmann et al; see appendix.¹⁶ This technique involves an axial oblique CT reconstruction in the line of femoral neck; a line is drawn from the anterior to posterior rim of the acetabulum. A

second line is drawn perpendicular from the first line to the center of the femoral head. The length of the second line is the acetabular depth.

Statistical Analysis

Summary statistics were used to describe each measure for cases and controls. For SEAs inter and intra-observer reliability was calculated by assessing the inter class correlation coefficient for absolute agreement. The SEA at each position around the acetabular axis was reported, for cases and controls, and means compared with an independent students t-test. As a measure of the validity of the SEA the following analysis were conducted:

- SEA at 12 o'clock was correlated (Pearson's test) with the CEA
- SEA depth was correlated with the acetabular depth (Pfirrmann method)
- SEA anteversion was correlated with the acetabular anteversion (Dandachli method)

The ROC, of measures where a statistical significance difference ($p < 0.05$) was identified in the SEA of cases and control, were plotted to determine which measures best-defined pincer morphology.

The measure with the greatest AUC was used to determine optimal threshold value. Threshold values were determined by calculating the value with the greatest Youdon's index (see Section 4.3 Statistical analysis).¹⁹³ Contingency tables were generated using this threshold value.

Sample Size

No information was available on the sensitivity and specificity of SEA, or other measures of pincer morphology such as CEA or cross over sign to help inform a sample size calculation. So similar to cam morphology I aimed to include 60 case hips and matched controls (2:1 matching ratio) as required in Section 4.3.2.

4.3.3 Results

Sampling

A flow diagram for the selection of subjects that were analysed is displayed in Figure 31, the demographics of these cases is shown in Table 16. In total only 27 subjects with pincer type FAI syndrome were identified. In order to reach the required sample size (n=60 hips) I also included subjects with mixed type FAI syndrome. Despite this only 29 subjects with pincer and mixed type FAI syndrome, who had undergone CT, were available for analysis as pincer cases. These cases were identified from 9/24 sites (13 surgeons).

Figure 31 Flow Diagram for selection of cases and controls to assess pincer morphology

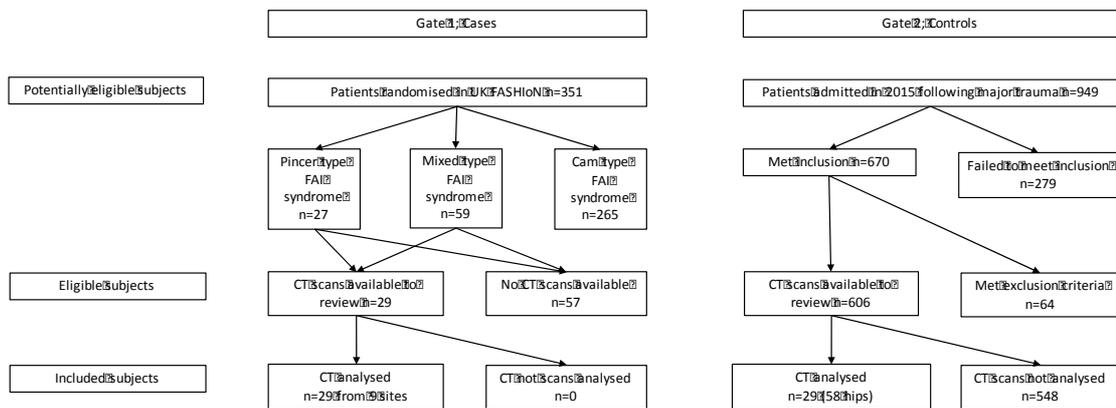


Table 16 Demographics of cases with mixed and pincer type FAI syndrome

	Mixed and Pincer cases	Controls
n	29 (pincer =14, mixed=15)	29 (58 hips)
Age	36 (SD 10.6)	36 (SD 10.6)
Sex	13 males, 16 females	13 males, 16 females

Image analysis

Acetabular Subtended Edge Angles

The inter, and intra-observer reliability of measuring SEA was 0.885 (95%CI 0.85-0.91) and 0.906 (95%CI 0.89-0.92) respectively. The standard error of measurement was 3.2°. Histograms showing the distribution in the SEA measurements around the acetabular axis are displayed in Figure 32.

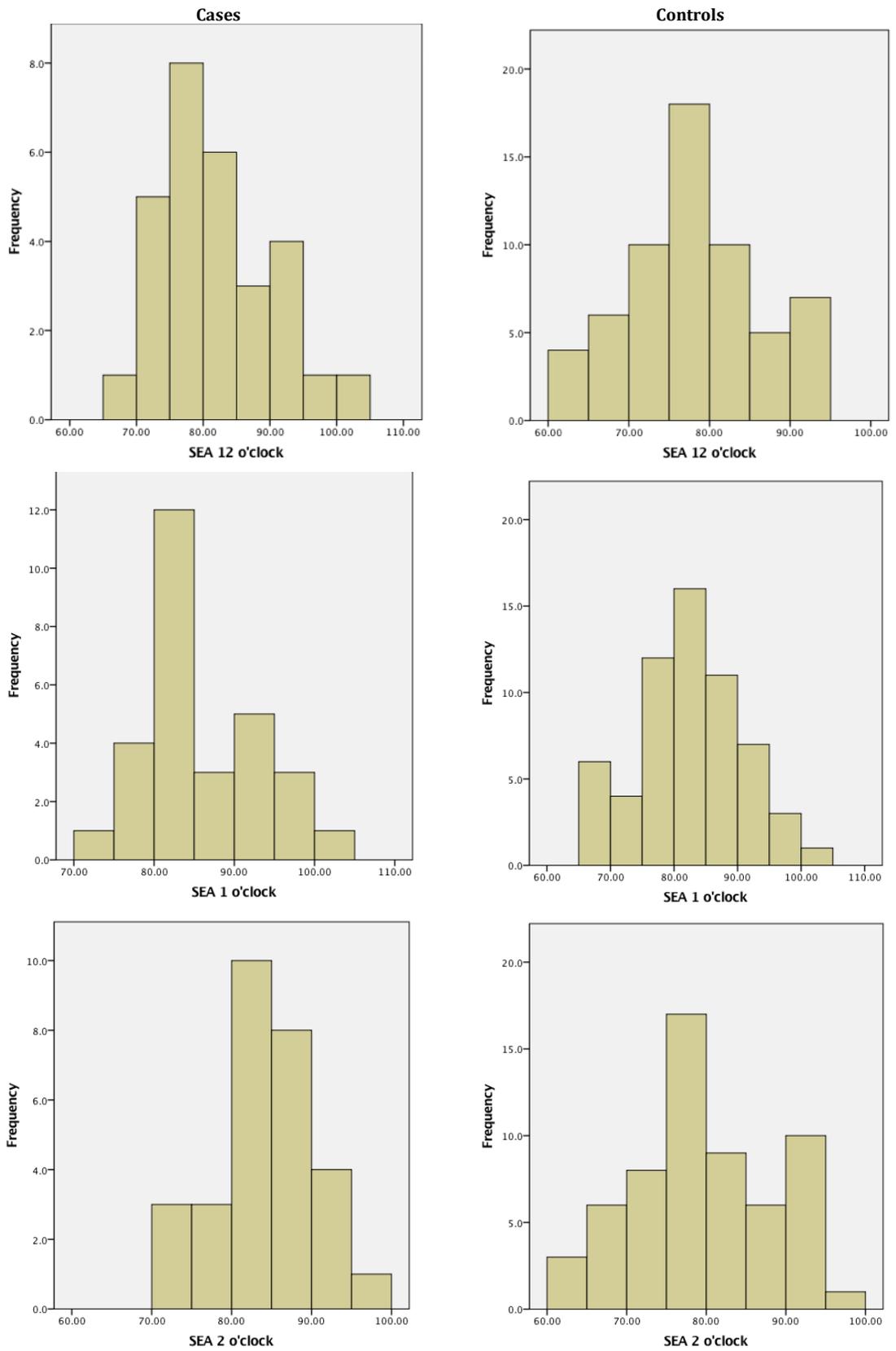
There was a strong correlation between the SEA measured at 12 o'clock and the CEA (Pearson's coefficient 0.92 $p < 0.001$), the SEA anteversion and conventional anteversion (0.74 $p < 0.001$), and SEA depth and Pfirrmann measured depth (0.89 $p < 0.001$).

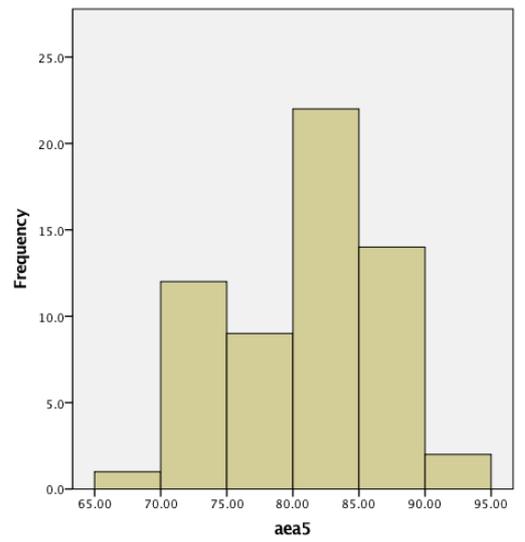
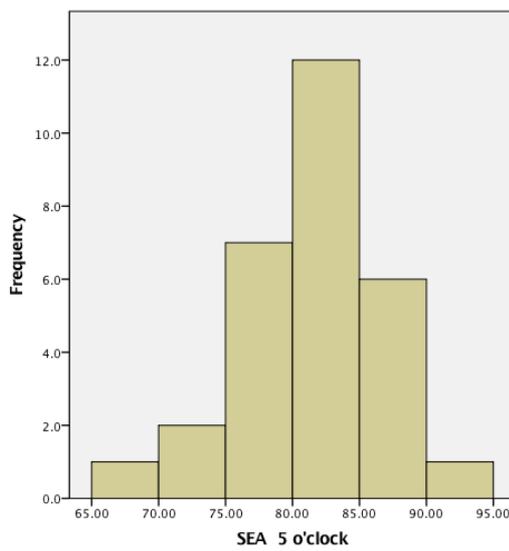
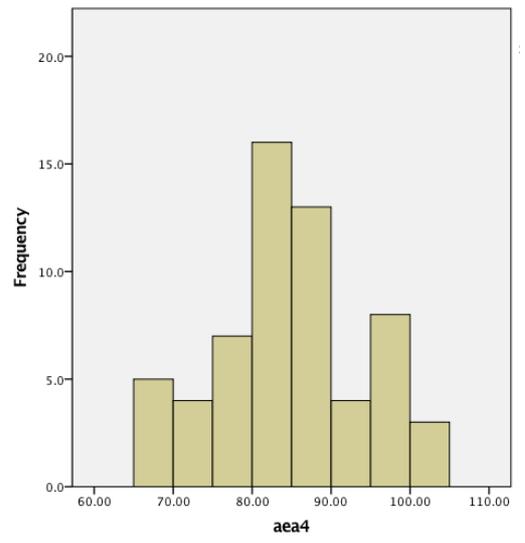
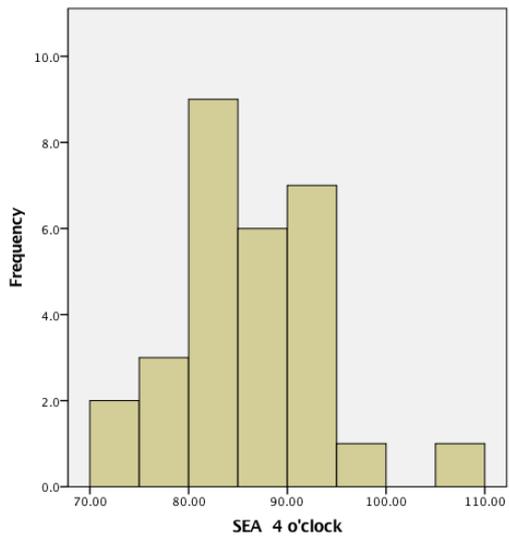
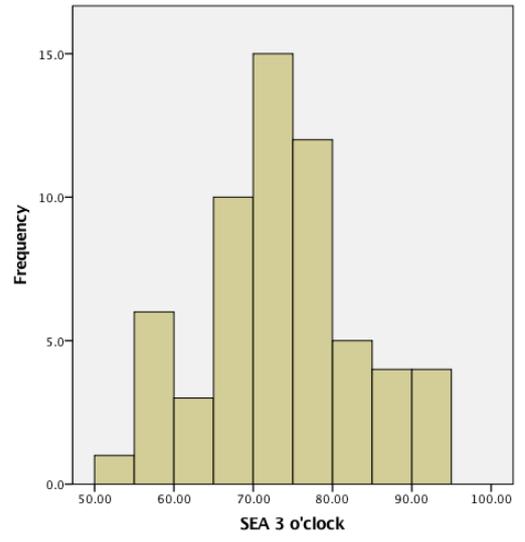
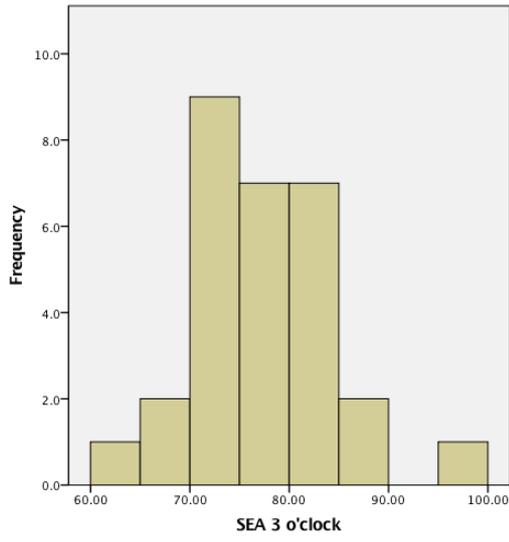
The mean SEA around the acetabular axis for cases and controls is displayed in Table 17. The mean SEAs were higher in the case group, reaching statistical significance at 12 and 2 o'clock. A visual representation of the SEAs around the acetabular axis of all pincer (and mixed) cases and controls is shown in the radar plot displayed in Figure 33, with mean SEAs displayed in Figure 34. Individual plots of SEA for cases and controls are displayed in the Appendix.

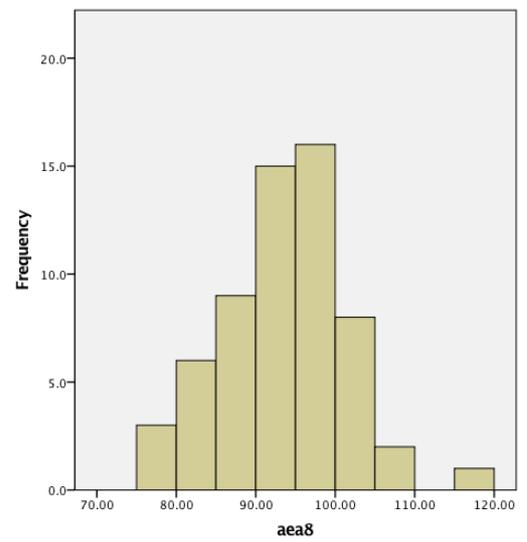
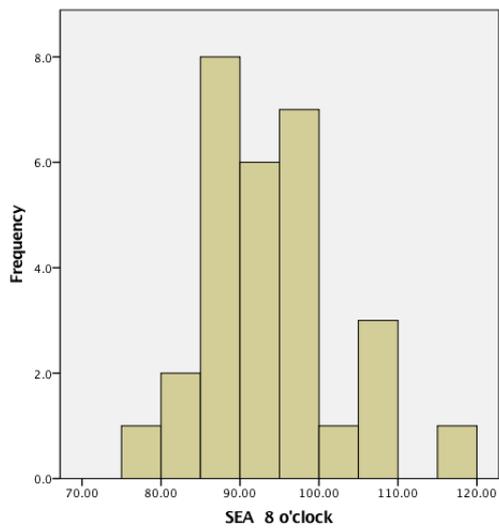
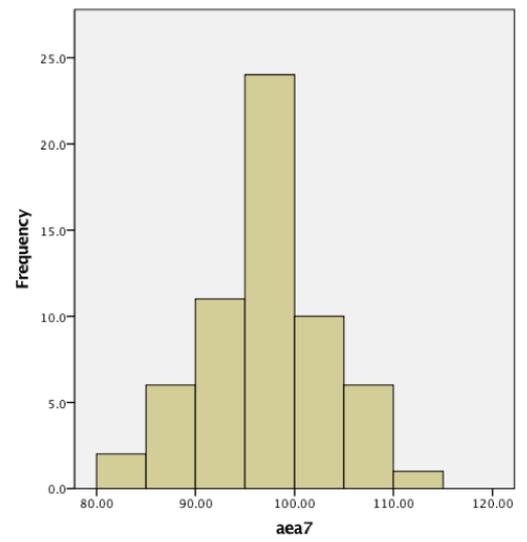
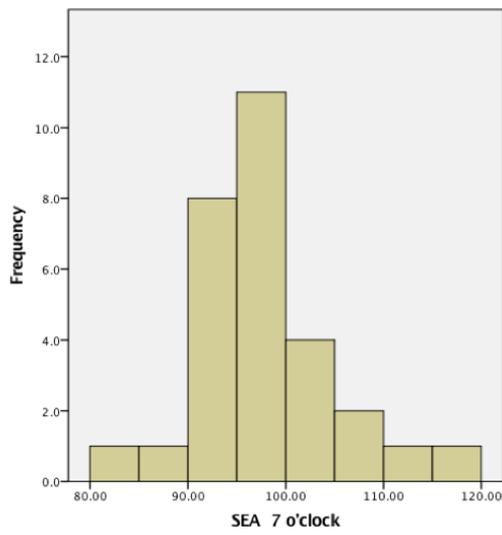
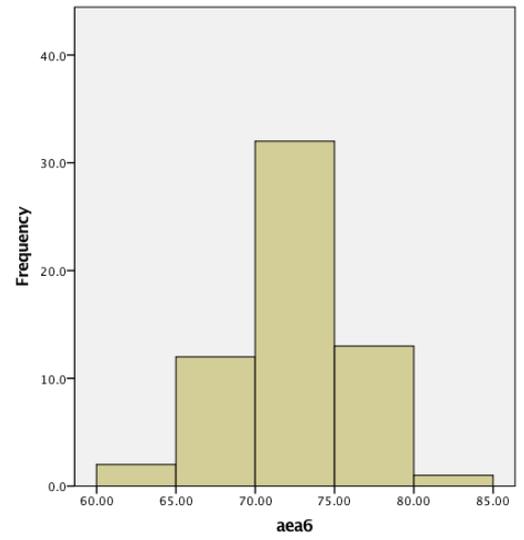
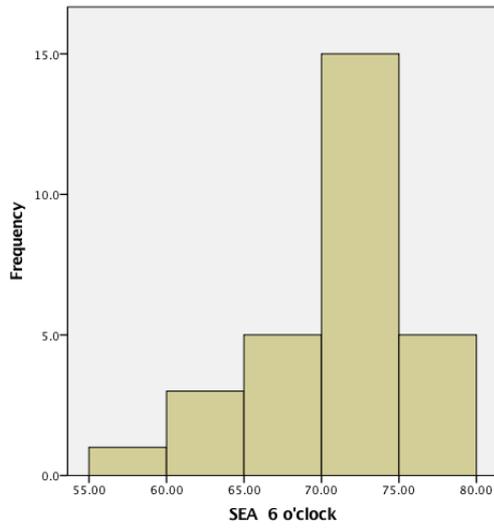
Table 17 Mean SEAs around the acetabular axis for cases and controls

Position on acetabular axis (o'clock)	Mean SEA/° (SD)												SEA Depth	SEA ante-version
	12	1	2	3	4	5	6	7	8	9	10	11		
Cases	82 (8.1)	85 (7.3)	84 (6.5)	77 (7.2)	85 (7.3)	81 (5.4)	71 (4.7)	98 (6.8)	93 (8.6)	82 (9.6)	78 (11.5)	77 (10.0)	74 (50.8)	0.994 (0.15)
Controls	78 (8.0)	82 (8.4)	79 (8.8)	73 (9.6)	84 (9.4)	81 (5.7)	72 (3.7)	97 (5.9)	93 (7.2)	81 (7.5)	74 (9.1)	73 (8.4)	72 (48.5)	1.02 (0.16)
p=	0.028	0.065	0.014	0.082	0.643	0.838	0.148	0.660	0.945	0.643	0.152	0.055	0.054	0.398
* = values that reached statistical significance at an of α 0.05														

Figure 32 Histograms of SEA measured around the acetabular axis, for cases and controls.







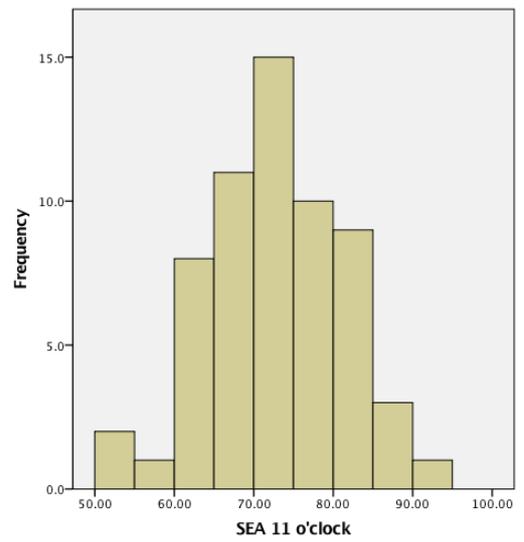
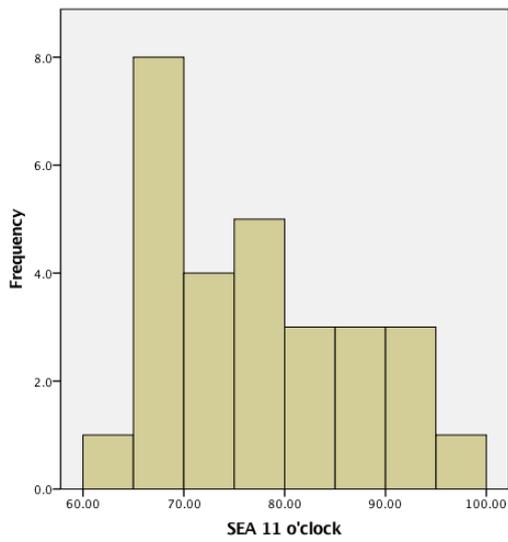
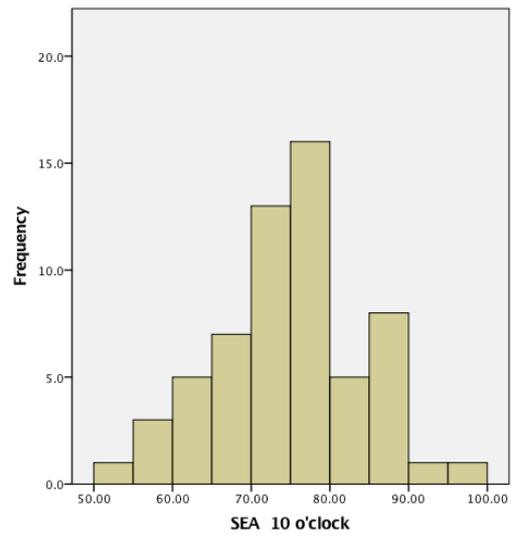
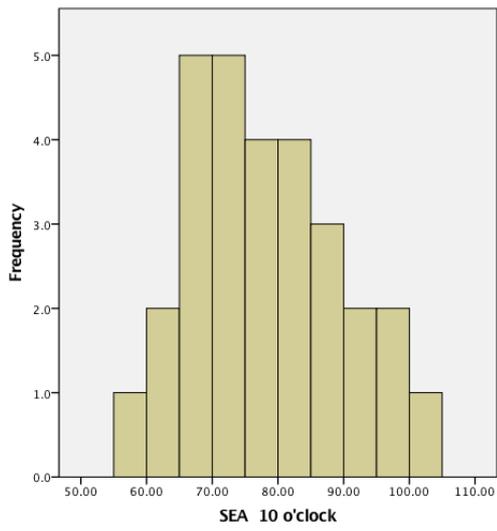
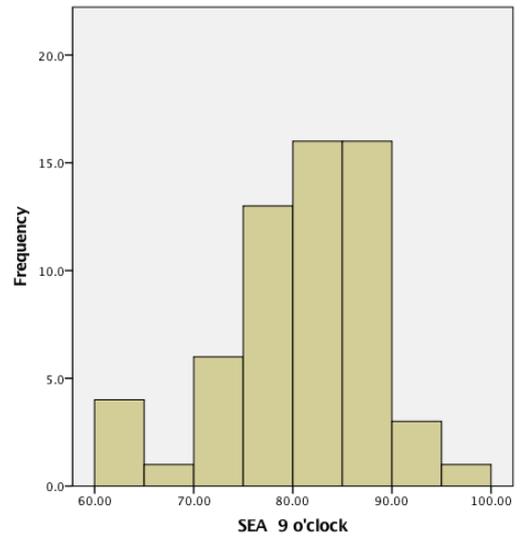
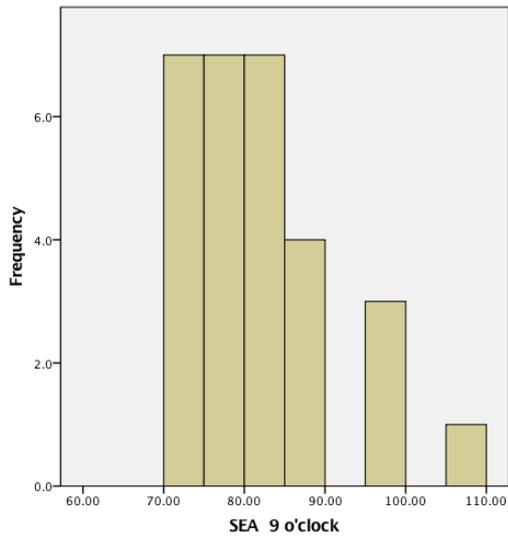
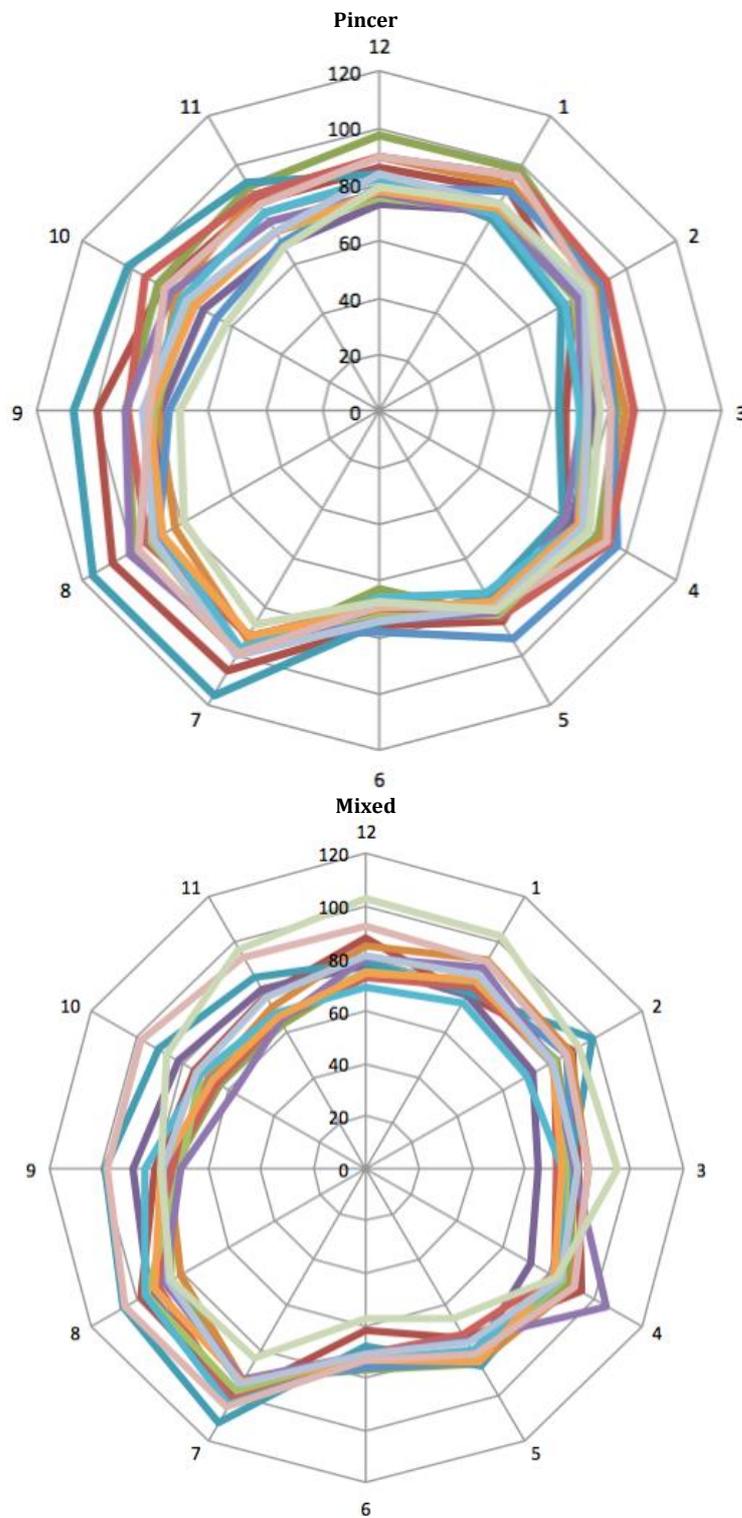


Figure 33 Radar plots of all pincer morphology case and control hips showing SEA measured around the acetabular axis. Cases that were defined and pincer and mixed type FAI syndrome are displayed separately.



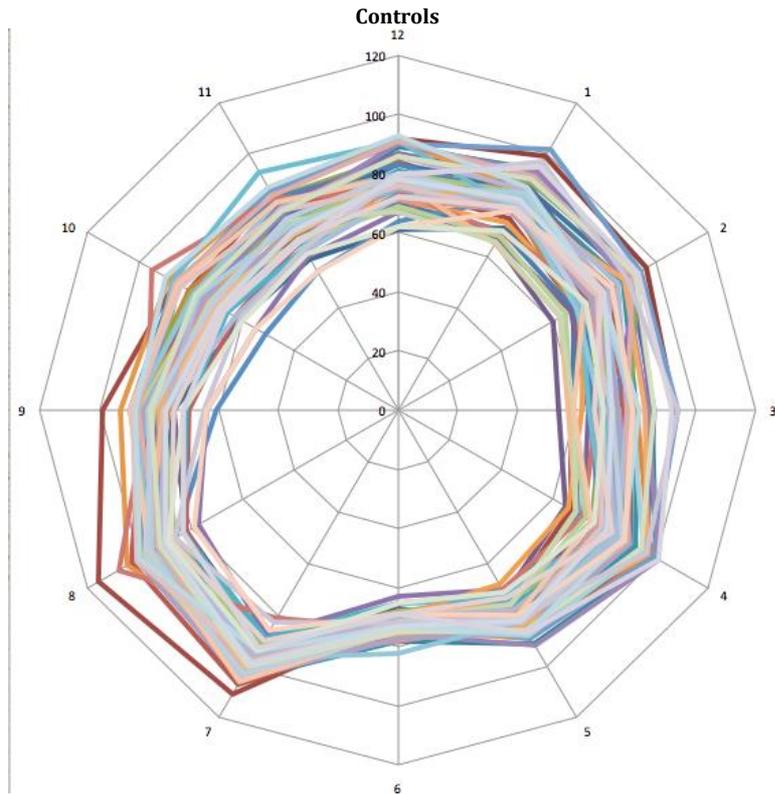
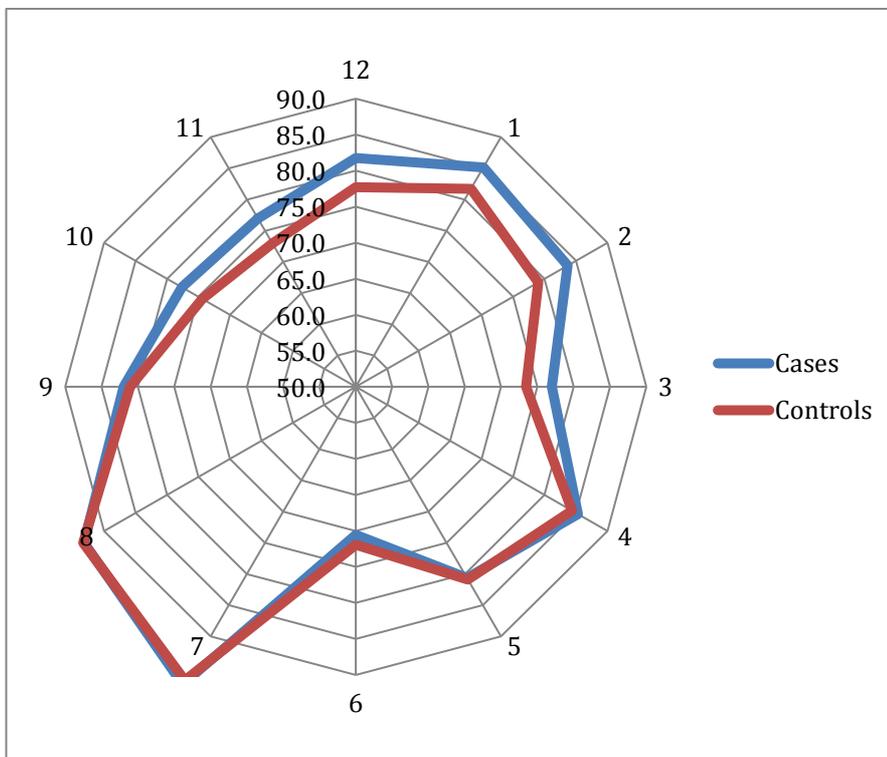


Figure 34 Radar plot of mean SEA for cases and controls measured around the acetabular axis



Other measures of pincer morphology

The mean CEAs, acetabular anteversion and acetabular depth for cases and controls is displayed in Table 18.

Table 18 Mean CEA, acetabular anteversion and acetabular depth for cases and controls

	CEA/° (SD)	Acetabular anteversion/° (SD)	Acetabular depth/ mm (SD)
Cases	34.9 (6.6)	18.3 (7.7)	4.7 (2.3)
Controls	33.2 (7.5)	20.8 (8.1)	6.0 (2.4)
p=	0.265	0.161	0.026*
* = values that reached statistical significance at an of α 0.05			

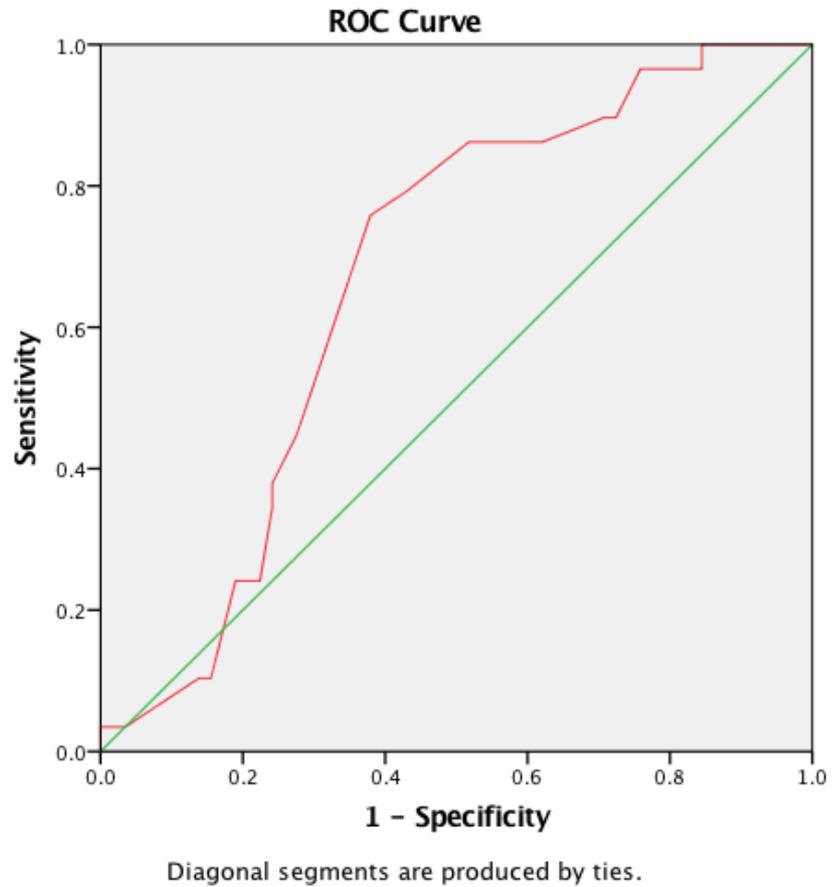
Receiver Operator Characteristics

The ROC was calculated for acetabular depth; the area under the curve was 0.62 (0.50-0.74). As the confidence interval crossed 0.5 the ROC curve was not plotted. ROCs were also calculated for the SEAs that reached statistical significance in Table 17. The resulting table for AUC and ROC curves are shown in Table 19 and Figure 35 respectively. The SEA measured at 2 o'clock had the best performing ROC with an AUC of 0.67 (95% CI: 0.55-0.78).

Table 19 AUC for measures of Pincer Morphology

Area Under the Curve					
Test Result Variable(s)	Area	Std. Error ^a	Asymptotic Sig. ^b	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
SEA 12 o'clock	0.62	0.062	0.063	0.50	0.74
SEA 2 o'clock	0.67	0.058	0.011	0.55	0.78
Acetabular depth	0.62	0.062	0.073	0.50	0.74
a. Under the nonparametric assumption					
b. Null hypothesis: true area = 0.5					

Figure 35 ROC Curve for assessment of pincer morphology using SEA at 2 o'clock



Youden's Index Pincer Morphology

The SEA at 2 o'clock had an AUC of 0.67. The optimal threshold for the SEA measured at 2 o'clock was calculated and was 80.5°. This yielded a sensitivity of 76% and a specificity of 62%.

Contingency Tables

Table 20 Contingency Tables for determining the presence of pincer morphology using a SEA at 2 o'clock greater than 80.5°

SEA at 2 o'clock >80.5°	Mixed or pincer type FAI syndrome		Sum
	+	-	
+	22	22	44
-	7	36	43
Sum	29	58	87
Sensitivity = 76% Specificity = 62% Positive predictive value = 50% Negative predictive value = 84%			

4.4 Discussion

4.4.1 Summary of Results

I have reported the ROC of a number of measures of cam and pincer morphology. The measure with the greatest AUC for cam morphology was a mean of α angles measured between 12 and 3 o'clock. A threshold value of 52° yielded a sensitivity of 82% and a specificity of 73% for determining the presence of cam morphology associated with FAI syndrome. When the SEA was measured at 2 o'clock, with a threshold value of 80.5°, the sensitivity and specificity for detecting pincer morphology associated with FAI syndrome was 76% and 62%.

4.4.2 Choice of Index test

In this chapter I attempted to build on previous research assessing cam morphology by assessing alpha angles at 30° intervals around the femoral head neck junction.⁶² Similar techniques have been used by other authors assessing cam morphology. Some of these methods were used to report point prevalence estimates in Chapter 2.^{94,124,125,138,158,200} By assessing the ROC of a diverse group of patients recruited by different surgeons in the FASHIoN trial, I believe I have built on the existing literature.

In this study, to assess pincer morphology I assessed a modification of the SEA method originally described in 2007.¹³ When I designed this study I did consider

using other tools of assessing acetabular morphology. Some of these tools were used in the studies reported in chapter 2; for example assessing acetabular version, depth and lateral CEAs on single slices of cross sectional imaging.^{16,124} However these measures did not fully characterise the acetabulum in the ways described in chapter 3. I therefore sought an additional method. I decided to assess the SEA method described in this chapter following discussion with my supervisor DG. Similar techniques that utilise computer modelling have also been developed and published. Initially Vandebussche reported the acetabular rim profile with a view to considering acetabular cup position in hip arthroplasty.¹³ More recently Cobb et al described a similar method in patients with FAI syndrome.¹⁴ Cobb et al's technique was semi automated, requiring a researcher to mark certain points on the acetabulum and then utilised a computer program to aid fitting of an acetabular model and measurements. The computer-programming element of this method was not available to me. The technique I used allowed me to make multiple measurements around the rim, from a consistent plane, without the necessity for computer modelling. The absence of computer modelling meant this process could be replicated using standard image viewing software available in outpatient clinics. What I feel distinguished my method to Vandebussche and Cobb was the axis around which the SEAs were measured. In my method this was a constant frame of reference (the *acetabular axis*; 45° abduction and 15° anteversion relative to anterior pelvic plane), where previous work measured around an axis that best fit the acetabular rim of each individual.¹⁴ I felt this offered potential advantages as it allowed an assessment of version, depth and rim morphology in one measure. However in reporting the results in the chapter I also reported SEA version and SEA depth as separate measures to the SEAs around the acetabular axis.

Other methods of assessing acetabular morphology that rely on computer programming have also been described. These include the method developed by Dandanchli et al.^{201,202} Dandachli characterised the acetabulum by superimposing its coverage onto a two-dimensional femoral head map, creating a value for the percentage of the femoral head covered by the acetabulum.^{201,202} The Clinical Graphics commercial software developed by Krekel, bases its outputs of rim morphology on the CEA, but measured around the acetabulum (not just as described

by Wiberg).^{67,203} Since starting my research a further method has also been developed by Bouma et al. In their manuscript they describe a measure called the 'omega zone'.²⁰⁴ This single measure offers much promise. In chapter 3 we recognised that FAI syndrome was the result of the complex interaction during motion between the proximal femur and acetabulum. The head neck profile, neck angle, torsion of the proximal femur and the depth, orientation and rim of the acetabulum were recognised to contribute to FAI syndrome and were known to be variable across the population. The omega zone attempts to measure each of these variables in different stages of hip motion.²⁰⁴ The omega zone builds on the work of Dandachli, who considered the percentage coverage of the femoral head by the acetabular rim. In calculating the omega zone the additional factors of neck shaft angle, alpha angle, antetorsion and motion are incorporated into the model.^{202,204} Bouma et al describe how the omega zone is reduced in subjects with cam type FAI syndrome but not in controls with either with or without cam morphology. This measure has the promise of capturing many important elements that may contribute to FAI syndrome. However, since their initial publication in 2015 no other manuscripts or commercial companies have used Bouma's method.

Some of the techniques described have assessed the acetabular rim with more precision than I was able to in my 12 SEA measurements per hip.^{13-15,201} By measuring more points around the rim these studies have been able to accurately demonstrate the true rim morphology.¹³ While measuring at 30° intervals around the femoral head neck junction was sufficient to characterise cam morphology, it is possibly too blunt a tool to accurately assess pincer morphology. Assessments with more measurements have been able to reconstruct the 3 troughs and peaks of the rim better than my SEA measurement.¹³

While each of these methods have their merits, they have not yet defined their ROC. The assessments thus far have been in populations of cases that were specifically pre-selected as having features of interest and in controls that were pre-selected as not having those features. Despite the impressive ability to model the acetabulum, without a defined diagnostic utility I would be unable to use these methods to determine the point prevalence of pincer morphology in the general population.

This is where my work in this chapter is original and makes a contribution to the literature. I attempted to use a robust methodological process to determine the diagnostic utility of a cross sectional measure of cam and pincer morphology.

4.4.3 Reference Standard

In this study the reference standard were those patients who had received a CT scan, diagnosed with FAI syndrome by a surgeon and randomised in the UK FASHIoN trial. With FAI syndrome there is no *gold standard* (e.g. histological) diagnosis with which to determine the accuracy of my index test. The subjects within FASHIoN provided a convenience sample, from a broad range of surgeons' practice, with which to evaluate the hip shapes that were associated with the diagnosis of FAI syndrome. Despite taking this pragmatic approach there is little detail about how the surgeons reached their diagnosis. The diagnostic criteria for FAI syndrome, established in Chapter 3, were published after recruitment to FASHIoN was complete. The FASHIoN trial is a pragmatic multicentre trial and is intended to reflect clinical practice for treating FAI syndrome across the UK. This includes the variations in what different surgeons consider to be cam or pincer morphology. However there are trial eligibility criteria, including radiographic measures (α angle $>55^\circ$ or CEA $>40^\circ$ or cross over sign). Despite these criteria there were cases within this study defined as cam and pincer morphology that did not reach these thresholds, indicating the pragmatic view taken by recruiting surgeons. Furthermore there was no evidence of a *cliff edge* in terms of diagnostic values around the thresholds set in the eligibility criteria.

A further issue relating to the reference standard population was that cases of FAI syndrome were identified by surgeons, who felt arthroscopic surgery was warranted. Other clinicians such as physiotherapists, sports physicians and radiologists may have different definitions of cam or pincer type FAI syndrome that have not been captured. There may also be cases that surgeons treat non-operatively or with open surgery that were excluded. These issues relate to the severity of the target disease being analysed and could contribute to false negatives.

When assessing pincer morphology I intended to assess the acetabular depth, orientation and rim. However, the reference standard used simply identified patients with pincer morphology and not which form of pincer the patient had (global over coverage, retroversion or focal over coverage respectively). This issue with the reference standard will have limited the discriminatory ability of the index test.

A further source of potential bias, that relates to the reference test, was the application of the clinical pathway in establishing the diagnosis.²⁰⁵ The reference subjects (cases) were patients in secondary care who had already seen a number of clinicians (e.g. GP or physiotherapist). The index test being proposed is to be used to assess subjects across the general population. It is possible that by identifying cases late in the clinical pathway the likelihood of a false positive was reduced.

In summary the subjects included that defined the true positives, were on balance not truly representative of subjects in the population with a diagnosis of cam or pincer type FAI syndrome.

Further sources of bias can be observed in the control, or disease free population. The control population was identified retrospectively from patients who had undergone a major trauma CT scan. Due to the retrospective nature of control selection I was unable to assess whether controls hips had FAI syndrome, or other causes of hip pain (co-morbid conditions), this may have contributed to false negatives.¹⁸⁹ The control subjects were matched by age and sex. However there was no matching for ethnicity. It has been suggested that there is a different prevalence of cam and pincer morphology in different ethnic groups.¹²⁰

The use of major trauma patients as a control population did mean that I was unable to evaluate subjects with hip pain but an alternative diagnosis (e.g. Perthes or SUFE; false positive) or subjects with co-morbid disease (e.g. hip OA; false positives or false negatives) in the same way that occurs in clinical practice.¹⁸⁹

These sources of bias that I have described, that affect the accuracy of the measures, are known as 'spectrum effects'. They are a common source of bias in studies of diagnostic accuracy.²⁰⁵ Spectrum effects describe the bias that comes from the variation in the test performance across different population subgroups and in the differencing prevalence of the disease across populations.

4.4.4 Index Test

In assessing α angles around the femoral head neck junction this study has further highlighted the limitations of measuring α angles at 12 o'clock alone, such as on an AP radiographs. The inadequacy of this has already been described and provided the motivation for me to assess α angles around the anterosuperior head neck junction.¹³⁸ When measuring at 12 o'clock on CT the AUC was 0.68, the optimal sensitivity and specificity were 65% and 61% respectively with a threshold value of 44°. It is worth noting that this threshold value is much lower than frequently used definitions such as 55, 63 and 78° which are likely to offer a superior specificity at the expense of sensitivity.^{94,103,160} The differences in the choice of thresholds may relate to spectrum effects or the different criteria set to determine the optimal value (e.g. clinically important, statistical and prognostic criteria).²⁰⁶ Another possible explanation is that there is over-diagnosis of FAI syndrome by surgeons. If this occurred in subjects recruited into the FASHIoN trial, and therefore the case subjects in this study, this would result in false positives in the sample of cases.

When the ROC for pincer morphology were measured the 95% confidence intervals for the AUC of CEA, acetabular depth, acetabular anteversion, SEA depth and SEA anteversion crossed 0.5. I therefore did not perform any additional analysis on these measures. It is worth noting that the confidence intervals for the AUC were *trending* towards statistical significance. I believe this is likely to have been a type 2 error due to the study only reaching half the required sample.

This study did not assess the diagnostic accuracy of the cross over sign. In chapter 2 I reported that the cross over sign was the most widely used measure of pincer morphology. However it is susceptible to measurement errors as it requires

appropriately centred radiographs without excessive pelvic tilt.^{45,137} The cross over sign is a measure that was reported to be highly prevalent in the population- raising the prospect of a large number of false positives.¹⁰⁵ I was unable to assess the cross over sign as I was assessing hip morphology on CT. I felt it was inappropriate to use a maximum intensity projection to assess for the presence of cross over sign as I could not reliably distinguish the anterior and posterior acetabular walls.

Other morphological features that were assessed and that have been described as playing a role in the development of FAI syndrome were NSA and antetorsion. NSA was not found to differentiate cases from controls. With respect to antetorsion I was unable to assess the ROC as no controls included axial cuts of the knees.

The SEA correlated well with the CEA, acetabular depth and anteversion. This isn't surprising as they are measuring similar aspects of acetabular morphology. SEA also had an excellent inter-rater reliability with a standard error of the measure of 3.2°. These facts suggest the measure is both valid and reliable. When considering validity, I reflected on whether the shape of the acetabulum shown in the radar plot Figure 34 mirrors what we consider an acetabulum to look like. At 3 o'clock in both cases and controls there is a reduced SEA, similar to what Vandebussche reported.¹³ This reduced SEA reflects the psoas notch. This is where the psoas tendon crosses the pelvic brim and courses over the front of the hip joint as it descends to the lesser trochanter.²⁰⁷ There is also an increase SEA at 7 and 8 o'clock. This reflects the posterior inferior margin of the acetabulum, or the ischial eminence.¹³

The SEA, when measured at 2 o'clock, performed better than existing measures of pincer morphology. I believe this is because it is assessing the area of the acetabulum where arthroscopic hip surgeons believe pincer type impingement arises and where they perform their rim resections. It was therefore able to objectively measure what surgeons may have subjectively assessed when diagnosing patients. The SEA is also able to measure around the axis of the acetabulum, detecting more subtle variation in shape. This is similar to the method of measuring α angles around the head neck junction, which proved superior to

taking a single measure at 12 o'clock. However in this study I do not believe I have fulfilled the full potential of the SEA.

In chapter 3 I report the important factors in assessing pincer morphology are depth, orientation and rim morphology of the acetabulum. The SEA can account for each of these. However, we were unable to distinguish between the subtle sub types of pincer morphology in the reference population. This may account for the reduced discriminatory ability of SEA depth and SEA anteversion. A further factor that may have affected the diagnostic utility of the SEA is understanding how more subtle forms of pincer morphology may be treated. Focal over coverage in an otherwise normally orientated acetabulum, assessed by measuring the rim (such as the SEA measure at 2 o'clock), is the most amenable type of pincer morphology to arthroscopic surgery. As described above under spectrum effects, arthroscopic surgery was the only treatment considered in the reference population. Global over coverage of the femoral head by the acetabulum (a deep acetabulum), which is best measured by the SEA depth, is far less amenable to arthroscopic treatment. These patients are more likely to be treated with a surgical hip dislocation and rim trimming if preservation surgery is being considered. Pincer morphology, as a consequence of a mal-orientated acetabulum, such as retroversion, would be best assessed by SEA anteversion. These patients would also be less likely to be treated by hip arthroscopy. Surgeons would typically elect for a reverse peri-acetabular osteotomy. I believe the reason the SEA depth and SEA anteversion did not perform as well as hoped may be due to a combination of spectrum effects and a type 2 error, not because the SEA lacks validity.

I consider it a strength that this study incorporated what different surgeons in different centres were pragmatically treating as cam and pincer type FAI syndrome. However, when I inspect some individual cases it does concern me that what a surgeon defined as cam morphology is not apparent when I inspected the imaging, with relatively low alpha angles around the head neck junction. Similarly some patients defined as having pincer (and mixed) type FAI syndrome do not show signs of over coverage, either focally, globally or as a consequence of acetabular retroversion. This may reflect the pragmatism of FASHIoN. Perhaps a patient had

FAI syndrome due to extreme ranges of motion, or another morphology I've not been able to consider such as low femoral neck antetorsion or reduced pelvic incidence.

Another possibility for the low alpha angles and SEAs in the cam and pincer cases respectively, were that surgeons were over diagnosing FAI syndrome. Over diagnosis may have occurred when surgeons incorrectly attributed patients' symptoms to FAI syndrome. By identifying what they thought was the presence of cam or pincer morphology, when these shapes were not truly present, nor the cause of the symptoms, surgeons may have inadvertently over diagnosed FAI syndrome. Over diagnosis would negatively affect the performance of the index tests, reducing the specificity of any threshold value I had determined due to the inclusion of false positives.

In my pincer morphology assessment I had to combine the *pure* pincer group with subjects identified by surgeons as having *mixed* cam and pincer morphology. Theoretically the surgeon should have positively identified the presence of cam and pincer morphology in these patients. Some authors raise concerns regarding the ability of cam and pincer morphology to co-exist.¹⁴ This concept is supported by the evolutionary development of mammal hip joints with two distinct sub groups recognised (Coxa recta and Coxa rotunda see introduction). By combining the pincer morphology group with cases that were identified as mixed impingement there is potential to have reduced any effect size of true pincer hip shapes. As the overall number of cases in each of these two groups was low, I have not been able to conduct any formal statistical between group analyses to assess if differences in the SEA exist.

4.4.5 Study Methodology

In addition to the sources of bias already discussed there were further methodological weaknesses in my approach. A two-gated (case control) diagnostic study with healthy controls is likely to produce results with inflated estimates of sensitivity and specificity due to spectrum effects and the lack of an alternative

diagnosis.¹⁸⁹ This study design is useful in screening different tests to identify potentially useful measures, but those tests should be repeated in a single gated (cohort) diagnostic accuracy study. A further methodological criticism is the fact that the analysis of the thresholds was conducted post hoc. Post hoc analysis can lead to 'data dredging'. To limit this I set out a priori rules by which I would judge each measure (e.g. using AUC and Youdens index).¹⁹⁰ In order to further validate the measures proposed a single gated (cohort) diagnostic accuracy study is necessary.^{189,190}

I performed a sample size calculation to determine the number of cases and controls I would require in this study. For this calculation I had to select an expected sensitivity and specificity. For cam morphology I was able to base this on previously research.¹⁵⁸ For pincer morphology there was no published research on the diagnostic utility for assessing pincer morphology for the measures I selected. However it seemed reasonable to expect a similar sensitivity and specificity for measures of pincer morphology and therefore I aimed to assess the same number of pincer cases as cam. Within the FASHIoN trial there were fewer pincer cases randomised and who had undergone a CT. Even when I bolstered this group with patients identified as mixed type FAI syndrome I still failed to achieve 60 cases.

My sample size calculation was performed in order to determine the confidence intervals of the AUC for a single measure. However, I used the results of this study to compare the AUC for different measures. In order to be powered to achieve this a different type of sample size calculation is required (with larger samples), which I did not perform.¹⁹⁴

This study adds to the literature by providing evidence to support which measures of cam and pincer morphology, should be used in epidemiological research. I report the optimal methods of utilising those measures and the threshold values which should be applied. Few other studies have assessed the ROC for measures of cam and pincer morphology. Sutter et al assessed 53 patients with cam or mixed type FAI syndrome and 53 controls. Interestingly Sutter et al also used a 55° α angle cut off to pre-select their case population who were all undergoing a surgical hip dislocation

in a single centre.¹⁵⁸ Sutter et al found the best ROC characteristics were when using a 55° threshold and measuring at the 1:30 o'clock position. This gave a sensitivity of 81% and a specificity of 65%. In this study I found a superior sensitivity and specificity when measuring the mean of α angles measured between 12 and 3 o'clock and 52° threshold.

4.4.6 Review of Objectives

In this study I intended to develop objective measures of both cam and pincer morphology that could be used to determine the number of subjects affected in the population. The test would not be used as part of a clinical pathway and therefore there would be no pre-test adjustment of probability of disease. I intended the measure be used in a population based prevalence study. In deciding an appropriate measure I had to consider the different methods of determining the thresholds with which to define disease. These include a statistical, prognostic or clinically important threshold.²⁰⁶ A statistical threshold is where a test is performed across a population and a predefined group (e.g. highest 5% of values) is used to define disease. A prognostic threshold would be used to predict the future development of disease (e.g. OA). A clinically important threshold is one that defines a clinical disorder, such as FAI syndrome. Given my objectives I felt this was the most appropriate approach.

I attempted to apply a clinically meaningful threshold by utilising a convenience sample of patients, who had been identified as having cam or pincer type FAI syndrome by surgeons in UK FASHIoN, and comparing their hip shapes to a convenience sample of age and sex matched controls. The definitions that resulted from this study must be taken in the context of the various sources of bias that result from the study's design which I have discussed.

The diagnostic utility of measuring the mean alpha angles between 12 and 3 o'clock offers a promising method to report the point prevalence of cam morphology in the general population. However the diagnostic utility of the SEA at 2 o'clock, although the best performing of the measured I assessed, was overall poor. The poor

performance of SEA may reflect that surgeons are not particularly adept at distinguishing *real* pincer type FAI syndrome from *non-diseased* subjects (i.e. over diagnosis). Indeed there is little difference in the radar plots of cases and controls with respect to pincer morphology. The differences are relatively modest and similar in magnitude to the standard error of the SEA measurement. It is questionable how useful SEA at 2 o'clock is when the positive predictive value of a measure greater than 80.5° is 50%. Comparing this value, to values previously reported by Cobb (mean SEA at any position 87°), 80.5° appears too small in magnitude to distinguish cases and controls.^{13,14} This will limit the use of this measure in a research setting to determine the point prevalence of pincer morphology, and in clinical practice to identify subjects with pincer type FAI syndrome.

4.5 Conclusion

Despite some methodological weaknesses this study proposes measures, with defined diagnostic utility, for future research to assess the prevalence of cam morphology in the population. Cam morphology assessed by measuring the mean α angle between 12 and 3 o'clock, using a 52° threshold yields a sensitivity of 82% and a specificity of 73%. Pincer morphology assessed by measuring the SEA at 2 o'clock, using an 80.5° threshold had the best performing receiver operator characteristics. Despite this, it had a limited ability to distinguish cases from controls. This will limit the use of this SEA for research to define the prevalence of pincer morphology in the population.

4.6 Reflections

This chapter has provided me the opportunity to understand how to design and conduct studies of diagnostic test accuracy. Gaining an appreciation for the subtleties of study design gives me greater confidence when interpreting other measures of disease. Through my reflections, I consider what I have learnt in conducting this research.

When I first considered my thesis plan I had not anticipated conducting this research. I (wrongly) believed that there were sufficiently robust definitions of cam and pincer morphology. I had intended to use one of the pre-existing definitions to define the prevalence of cam and pincer morphology in the population. Through the work I conducted in chapters 2 and 3, it became apparent that I needed definitions with an established diagnostic accuracy. In planning this study I had not fully appreciated the subtleties involved in the design of studies of diagnostic accuracy. With hindsight, and with what I have since learnt, I now appreciate that I did not design this study as robustly as was possible. The STARD and QUADAS guidelines provide useful tools which highlight important aspects to consider, I have used these to critique my own work in the discussion.¹⁹⁰ The design I chose was a case control study. This is not technically a correct use of the term as a case control study is an etiological study that is longitudinal. Studies of diagnostic accuracy are cross sectional. This is where the term 'multi-gated' emerges, effectively to mean a case control cross sectional study of diagnostic accuracy; where there are different gates of entry to the study to define cases and controls. In this study both cases and controls were from convenience samples. It is reasonable to use these populations; especially in the early stages of evaluating a diagnostic test given they require fewer resources to collect and analyse data. With hindsight at the planning stage, I do not think I had fully appreciated the consequent bias of using these populations. Despite these issues the samples did provide an approach to evaluation that was able to indicate which measures were suitable for further evaluation.

It is now evident that I attempted to evaluate too many tests in this study. This is reflected in the length and complexity of this chapter. It seemed any easy extension to assess just one more measure (e.g. NSA) having identified the populations and obtained their imaging. I believe it was a mistake to assess so many measures, it undermined the sample size calculation and blurred the objectives. I partly chose to evaluate more measures to compare new tools such as SEA in the context of the performance of older measures such as acetabular depth and CEAs.

In this chapter I encountered a number of challenges that occur in studies of diagnostic accuracy. These challenges include identifying a suitable reference standard, the clinical pathway within which the test will be conducted and spectrum effects. These challenges are not unique to this study and are frequently encountered in other studies of diagnostic accuracy. When analysing the results of this study and in trying to identify sources of potential bias I became increasingly aware of methodological weaknesses in my study design. Many of these stem from the research questions which were ultimately looking to answer a circular issue. How do you distinguish a group, identified as having certain morphological features, with a measure of morphology? It seemed a valid question to pose, as I was not certain all clinicians considered the same shapes pathological. In order to understand the population at risk of FAI syndrome, (where the presence of abnormal hip morphology is required for diagnosis) I needed to understand what objective measure could be used to define, what clinicians subjectively considered cam or pincer morphology. This entailed attempting to resolve this circular issue. This resulted in a bias in the selection of my reference standard population; an issue that I believed to be the greatest source of potential bias. In this study there were three issues with the selection of the reference standard:

- 1. Clinicians would use hip shape characteristics observed on diagnostic imaging to diagnose disease (circular diagnostic issue).*
- 2. Only subjects seen by surgeons and considered suitable for arthroscopic surgery were included (therefore only small spectrum of disease severity).*
- 3. The eligibility criteria for UK FASHIoN (although pragmatic does stipulate imaging criteria).*

Another significant source of bias was in the methodology. Being retrospective and using a multi-gated design meant the estimates of diagnostic accuracy were likely to be inflated. Through conducting this research I now understand that no single study can fully evaluate a diagnostic test. The sources of bias I identified require that the tests are reassessed. In this way testing diagnostic criteria is much like the assessment of treatments, they requires on-going evaluation in different populations (e.g. IDEAL framework of surgical innovation).²⁰⁸ In the assessment of diagnostic studies a four phase development has been proposed:²⁰⁹

- *Phase 1: studies comparing test distribution between substantially diseased and healthy controls*
- *Phase 2: evaluation in different types of diseased subjects (spectrum effects, differing degrees of disease severity)*
- *Phase 3: further evaluation that includes greater variation in disease severity, co-morbidities and clinical presentation*
- *Phase 4: Prospectively evaluate the test in a large series within the pathway where the test will be conducted.*

Using this framework I have evaluated the first phase only. In a phase 2 study I might wish to evaluate patients assessed by surgeons and treated with either arthroscopic surgery (not using the FASHIoN inclusion criteria), open surgery or conservative care. In a phase three study I would want to include subjects treated by sports physicians, physiotherapists and surgeons. The panel members that participated in Chapter 3 would provide a useful range of clinical practice with which to make assessments that encompassed a wide variety of disease severity and clinical settings. This degree of evaluation and verification may be sufficient to answer my research question. A phase four prospective assessment in the general population may not be feasible. Anecdotally FAI syndrome appears to have a low point prevalence in the general population, the test (CT) is invasive (using ionising radiation), time consuming and relatively expensive. These factors make assessment in a general population setting not practical to answer the research question posed. One approach to resolving these issues would be to assess patients who have already undergone CT and prospectively assess their symptoms and clinical signs. However, a subjective clinician assessment of imaging for the presence of cam or pincer morphology in order to diagnose FAI syndrome would still be required.

In this study I set out to define how cam and pincer morphology should be defined in order to determine their prevalence in the general population. A further use of these diagnostic tests (with different thresholds) could be to determine the morphology of cases with FAI syndrome with poorer prognostic features such as the development of OA or a negative response to treatment. Evaluation under these terms clearly requires new verification studies of the test. It is conceivable that SEAs or α angles could be

used to identify subjects who are more likely to have a superior outcome with a particular intervention.

A further application of the SEA that I have not considered in this thesis is their use in the evaluation of hip dysplasia. Similar measures of hip morphology are used to define dysplasia, although with different thresholds e.g. CEA <19°. Outside this thesis, with the knowledge I have gained from conducting this chapter, I would like to make this evaluation. It is possible that more subtle forms of dysplasia (e.g. anterior under-coverage) are more easily defined with a SEA than a CEA or subjective interpretation of the anterior wall on an AP radiograph. The SEA could also be used in surgical planning of a peri-acetabular osteotomy.

Measuring multiple α angles around the head neck junction or SEAs around the acetabular axis is time consuming. In this study I performed the task manually. For these definitions to be applied in routine practice automation is required. I did explore with computer scientists at the university a method to perform this automatically, using a technique we'd developed.²¹⁰ However we were unsuccessful in applying this to the SEA. Commercially available image analysis tools such as 'clinical graphics' have been able to offer a similar automated image analysis service.²⁰⁰

In conclusion, this study has presented a number of challenges in understanding the methodology of research into diagnostic accuracy. While in my discussion I am critical of my approach, this has allowed me to learn lessons that I can apply in future research and in interpreting other authors work.

5 Prevalence of Cam Morphology in the General Population

In this chapter I use the definitions developed in chapter 4 to estimate the prevalence of cam and pincer morphology in the general population.

Declaration

I received the following help in writing this chapter:

H Parsons; provided statistical advise on conducting a sample size calculation

This work has been presented at a national conference:

Title: Definition and Epidemiology of FAI Syndrome. Presenter: E Dickenson. Event: Sports Hip Meeting, June 2016.

This study was sponsored by University Hospitals Coventry and Warwickshire. NHS Research Ethics Committee approval was obtained for this study (14/NI/1078).

5.1 Introduction

In chapter 2 I attempted to determine the prevalence of the cam and pincer morphology in the general population.¹⁴⁸ Due to the lack of clear diagnostic criteria and of truly general population based studies, I was unable to estimate the prevalence of cam or pincer morphology. In chapter 3 and 4 I have attempted to use scientific methods to define FAI syndrome and how to define cam and pincer morphology. In chapter 4 I was able to propose a diagnostic test with a robust utility to determine the prevalence of cam morphology. However I do not feel the performance of the SEA was adequate to apply this definition in the population. I therefore intend to apply the diagnostic criteria developed for cam morphology to estimate the point prevalence of cam morphology in the population.

5.2 Objectives

- To determine the point prevalence of cam morphology in the general population
- To report the distribution of SEAs measured at 2 o'clock in the general population

5.3 Methods

Institutional and NHS research ethics committee approval was sought prior to conducting this research (14/NI/1078).

I conducted a single centre retrospective cross sectional study of patients who had undergone a major trauma CT scan in order to determine the point prevalence of cam and pincer morphology.

5.3.1 Population

All patients who presented to UHCW in 2015 and received a CT scan following major trauma were screened. UHCW is the second busiest major trauma centre nationally and receives patients from across the midlands region of the United Kingdom.²¹¹

Major trauma is defined as an injury severity score of greater than 9.²¹²

5.3.2 Eligibility Criteria

Inclusions Criteria

The following subjects were included:

- Patients aged 16 to 65 years
- Patients who had undergone a CT scan for major trauma that included the pelvis

Exclusion Criteria

The following exclusion criteria were applied

- Patient death
- Any pelvic, acetabular or proximal femoral fractures.

5.3.3 Sampling

A random sample, using random number generation, of eligible participants was selected so that equal numbers of male and females were included from each of the following age categories:

- 16-25 years
- 26-35 years
- 36-45 years
- 46-55 years
- 56-65 years

5.3.4 Data Collection

Selected participants' date of birth, ethnicity, postcode, date of CT scan, and CT DICOM files were collected.

5.3.5 Outcomes Measures

Sample Characteristics

I chose to collect data that would enable me report whether the study sample was broadly representative of the general population. I used the modified risk of bias tool for prevalence studies (used to assess study risk of bias in chapter 2) to determine which factors I should assess.¹⁰¹

Ethnicity

Ethnicity was self-reported by participants when they were registered at UHCW. The breakdown in the ethnicity of the study sample was compared to the UK population data from the 2011 census.²¹³

Ethnicity has been reported to affect the prevalence of cam morphology. ^{108,112,120,128}

Index of Multiple Deprivation

Participant postcodes were used to identify their index of multiple deprivation (IMD) and their rural urban classification from 2011 UK Government census data.²¹⁴

The IMD is the official measure of relative deprivation for neighbourhoods in England.²¹⁴ The IMD is based on 7 domains: income (22.5%), employment (22.5%), education (13.5%), health (13.5%), crime (9.3%), barriers to housing and services (9.3%), living environment (9.3%). Areas are ranked in deciles according to these measures.

Presently there is no evidence that hip morphology differs between subjects from different areas of deprivation. I chose to collect this outcome measure to assess

whether my sample was representative of the general population. This was intended to satisfy the criteria of the modified risk of bias tool.¹⁰¹

Rural Urban Classification

The rural urban classification is a measure of the population density of an area. Each area is assigned according to the subjects postcode as:

- A1 Major Conurbation
- B1 Minor Conurbation
- C1 City and Town
- C2 City and Town in a sparse setting
- D1 Town and Fringe
- D2 Town and Fringe in a sparse setting
- E1 Village
- E2 Village in a sparse setting
- F1 Hamlets and isolated dwellings
- F2 Hamlets and isolated dwellings in a sparse setting

Presently there is no evidence that hip morphology differs between urban and rural subjects. I chose to collect this outcome measure to assess whether my sample was representative of the general population, including subjects from both a rural and urban setting, as stated in the modified risk of bias tool.¹⁰¹

Assessment of Hip Morphology

Cam Morphology

α angles were measured as described in chapter 4. Cam morphology was defined as a mean α angle between 12 and 3 o'clock greater than 52°.

Pincer Morphology

Subtended edge angles (SEA) were measured as described in chapter 4. The population distribution of SEAs measured at 2 o'clock was reported. Pincer morphology was defined as a SEA measured at 2 o'clock that was greater than 80.5°.

However, given the reservations regarding this measures diagnostic accuracy no conclusions were drawn from this data.

Hip Osteoarthritis

The presence of hip osteoarthritis, especially osteophytes, may affect measurements of hip morphology. The presence of hip osteophytes at the acetabular margin, femoral head neck junction and cotyloid fossa were recorded.

5.3.6 Image Analysis

Images were analysed using OsiriX Dicom viewer (Geneva, Switzerland) version 8.0.1.¹⁹¹

5.3.7 Statistical Analysis

Summary statistics were generated to report the prevalence of cam and pincer morphology as a proportion of participants and hips affected quoting 95% confidence intervals.²¹⁵ A secondary analysis excluding hips and subjects with osteophytes was also conducted.

5.3.8 Sample Size

A sample size calculation was performed in order to establish the number of participants that would be required to estimate the point prevalence with a power (β) of 0.8 and a confidence (α) of 0.05. I used the study by Hack et al to estimate the constant proportion (the anticipated prevalence of cam morphology- 34%) for the sample size calculation.⁹⁴ Table 21 shows the range of sample sizes for a given confidence interval widths and constant proportions for a confidence level of 0.05 and a power of 0.8.¹⁹⁵ I decided to include 200 participants, this will provide sufficient power for a confidence interval width of 0.1 anticipating a prevalence of 0.35 and will allow equal numbers of males and females of the 5 different age groups.

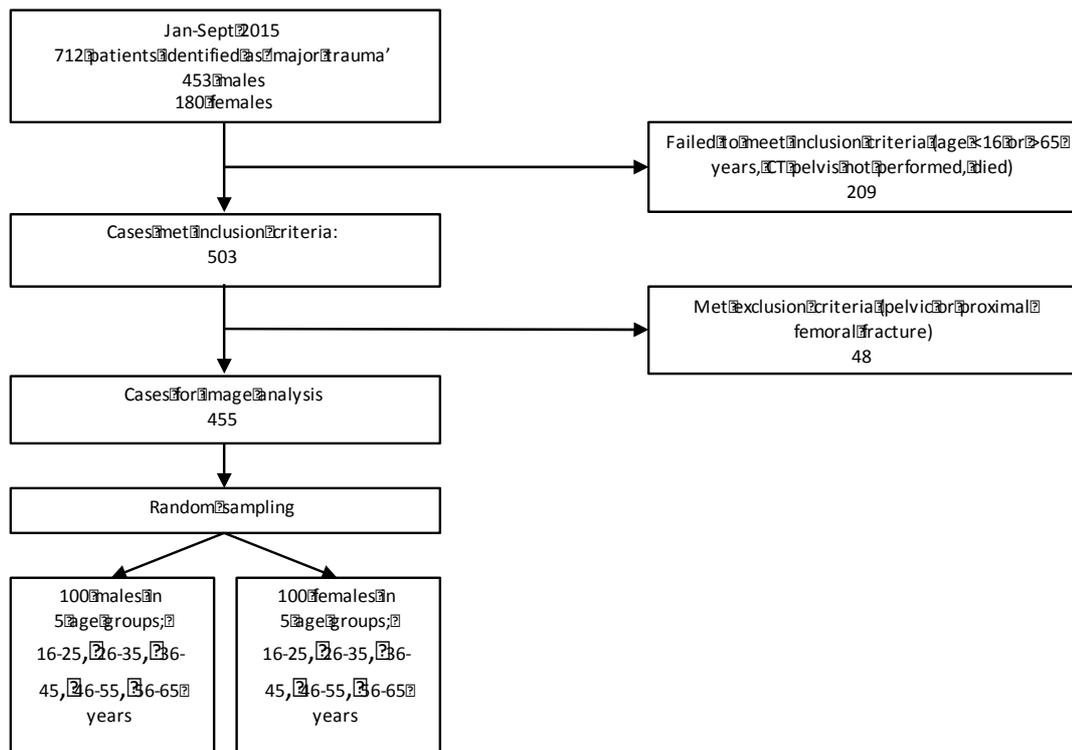
Table 21 Range of sample sizes for given prevalence estimate and confidence interval width

Anticipated prevalence (constant proportion)	Width of 95% Confidence interval		
	0.08	0.1	0.12
0.3	280	183	127
0.35	295	192	133
0.4	304	195	140

5.4 Results

The 2015 UHCW major trauma database was screened over consecutive months. After nine months, a sufficient number of subjects had been identified to allow random sampling. Figure 36 shows how the sample was identified.

Figure 36 Flow Diagram



5.4.1 Participant Characteristics

Ethnicity

Of the 200 participants identified 181 had their ethnicity recorded. The majority of patients were white. The ethnicity of the included subjects is displayed in Table 22.

Table 22 Ethnicity of included subjects

Ethnicity	Number of subjects	% of subjects who stated ethnicity	% of UK General Population (2011 census data) ²¹³
White including: 1. English/ Welsh/ Scottish/ Northern Irish/ British 2. Irish 3. Gypsy or Irish Traveller 4. Any other White background	155	85.6	86
Mixed/ Multiple ethnic groups including: 5. White and Black Caribbean 6. White and Black African 7. White and Asian 8. Any other Mixed/Multiple ethnic background	2	1.1	2.2
Asian/ Asian including: 9. Indian 10. Pakistani 11. Bangladeshi 12. Chinese 13. Any other Asian	10	5.5	7.5
Black/ African/Caribbean/Black British including: 14. African 15. Caribbean 16. Any other Black/African/Caribbean background	1	0.6	3.3
Other ethnic group including: 17. Arab 18. Any other ethnic group	13	7.2	1
Not stated	19	n/a	n/a
n/a = not applicable			

Index of Multiple Deprivation

There was a broad representation in the sample from the most to the least deprived areas based on the IMD; see Table 23.

Table 23 English Index of Multiple Deprivation 2015

IMD decile	% of Participants
Most deprived - 1	11
2	10
3	11
4	9
5	10
6	10
7	8
8	9
9	8
Least deprived - 10	9
No data	7

Rural Urban Classification

The majority of participants lived in an urban setting (79%). The balance between rural and urban population is listed in Table 24, the majority of patients (65%) were classified as living in a C1 area, which represents a city or town.

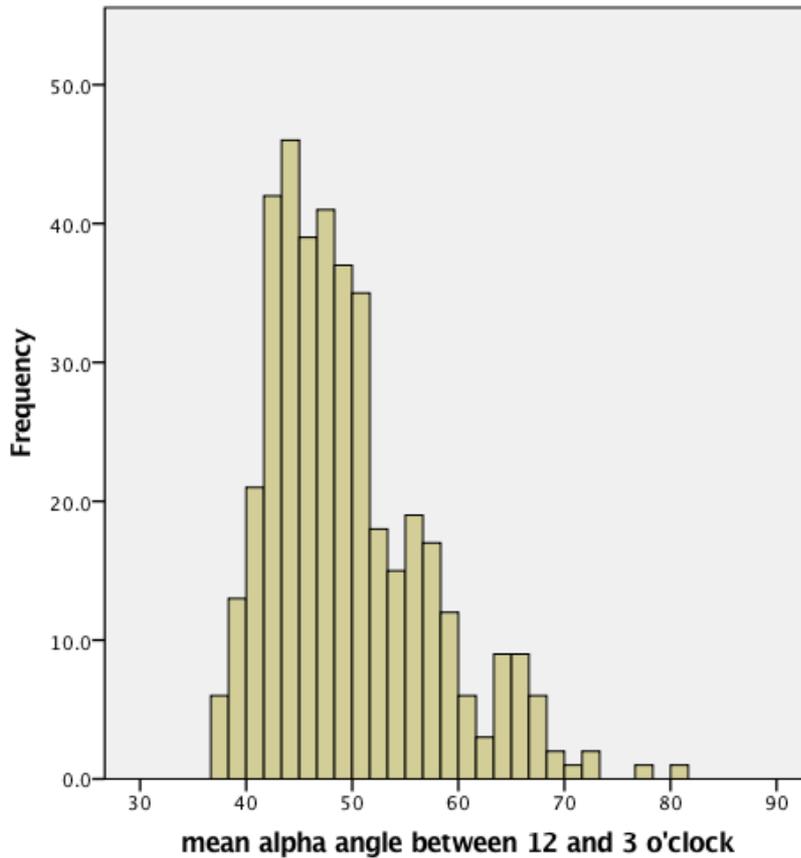
Table 24 Rural Urban Classification

Rural urban classification	% of all cases
A1 – Major Conurbation	8.0
B1 – Minor conurbation	0.5
C1 – City and town	65.0
C2 – City and town in sparse setting	0.5
D1 – Town and fringe	12.5
D2 – Town and fringe in sparse setting	0.0
E1 – Village	6.0
E2 – Village in sparse setting	0.0
F1 - Hamlets and isolated dwellings	1.5
F2 - Hamlets and isolated dwellings in sparse setting	0.0
No data	6.0

5.4.2 Cam Morphology

The population distribution of the mean of alpha angles measured between 12 and 3 o'clock is displayed in Figure 37. The prevalence of cam morphology in the population sampled was 41% (95%CI 36-45), with 51% of men and 30% of women affected (see Table 25). The prevalence of cam morphology at different ages and in men and women is displayed in Table 25. Thirty-five patients (21 male), including 68 hips (40 male), were identified as having radiographic OA. The prevalence of cam morphology, excluding subjects with osteophytes, was 35% (95%CI 27-42) (males 44% females 26%).

Figure 37 The population distribution of the mean of alpha angles measured between 12 and 3 o'clock



5.4.3 Prevalence of Pincer Morphology

The population distribution of the SEA measured at 2 o'clock is displayed in Figure 38. The prevalence of pincer morphology in the population sampled, using the 80.5 threshold at 2 o'clock was 54% (95%CI 49-59), with 60% of men and 48% of women affected (see Table 26). The prevalence of pincer morphology at different ages and in men and women is displayed in Table 26. The prevalence of pincer morphology, excluding subjects with radiographic OA, was 47% (95%CI 39-54)(males 52% females 42%).

Figure 38 The population distribution of the SEA measured at 2 o'clock

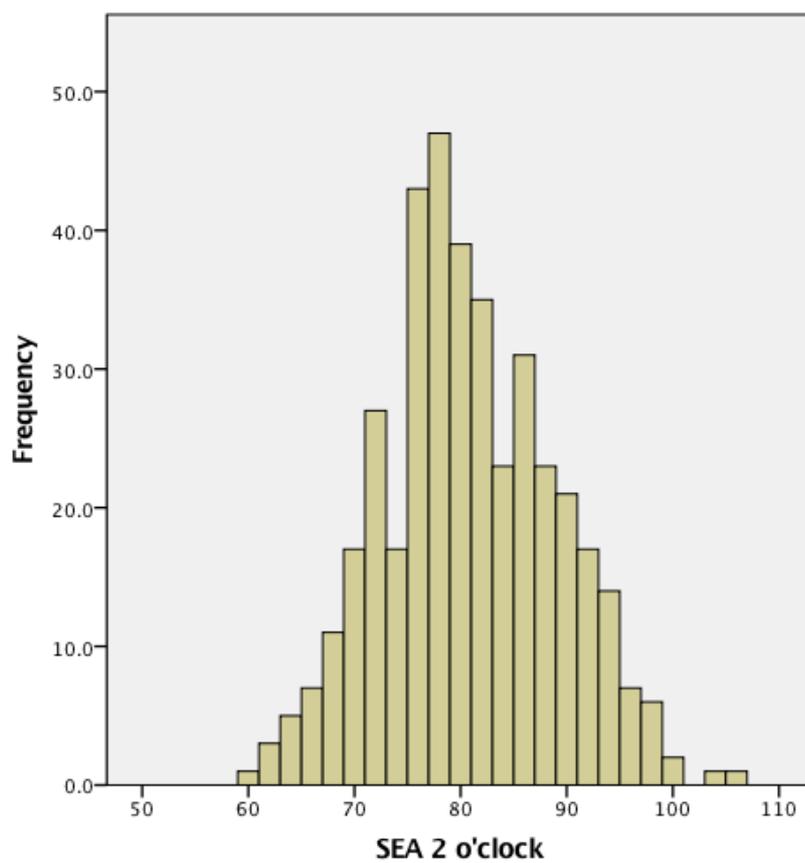


Table 25 Prevalence of cam morphology

Population and age group, years	Number of hips affected	Prevalence of Hips affected, %	Number of participants affected	Prevalence of participants affected, %
Males and females aged 16-65 years	123	31	81	41
Males				
16-25	16	44	9	45
26-35	9	23	5	30
36-45	16	40	10	50
46-55	16	40	14	70
56-65	19	48	13	65
16-65	76	38	51	51
Females				
16-25	2	5	2	10
26-35	6	15	5	25
36-45	16	18	5	25
46-55	15	38	12	60
56-65	8	18	6	30
16-65	47	24	30	30
Excluding cases of OA				
Males and females aged 16-65	96	29	57	35
Males aged 16-65	57	36	35	44
Female aged 16-65	39	23	22	26

Table 26 Prevalence of pincer morphology in hips and participants

Population and age group, years	Number of hips affected	Prevalence of Hips affected, %	Number of participants affected	Prevalence of participants affected, %
Males and females aged 16-65	187	47	108	54
Males				
16-25	12	30	8	40
26-35	20	50	12	60
36-45	18	45	10	50
46-55	23	58	13	65
56-65	31	78	17	85
16-65	104	52	60	60
Females				
16-25	14	35	11	55
26-35	10	25	6	30
36-45	18	45	7	35
46-55	13	33	8	42
56-65	28	70	16	80
16-65	83	42	48	48
Excluding cases of OA				
Males and females aged 16-65	142	43	77	47
Males aged 16-65	79	49	41	52
Female aged 16-65	63	37	36	42

5.5 Discussion

I report the prevalence of cam and pincer morphology in a sample that is broadly representative of the UK general population. Cam morphology was identified in 41% of subjects' aged 16-65 (males 51% and females 30%).

This study was a retrospective cross sectional study utilising a moderate sized, convenience sample from a clinical population. By sampling equal numbers of men and women of different ages, by reporting the ethnicity, IMD and rural urban classification I intended to demonstrate that the sample was broadly representative of the general population. The fact that the sampling frame was a clinical population (those undergoing a major trauma CT scan) introduces a potential source of bias in the prevalence estimate.¹⁰¹ Being involved in a major trauma event is, to a certain extent, random in its nature. Although it is recognised that young males are more frequently affected.²¹⁶ The incidence of acetabular fractures (a group excluded in my

study), and posterior instability is reported to be higher amongst those with cam and pincer morphology; this is a potential source of bias, which may result in an under estimate of the true prevalence.^{217,218} However any effect of this bias on the overall prevalence estimate is likely to be small given the low incidence of these injuries.

In this study I did not report the prevalence of cam and pincer morphology by sub groups of patients, for example ethnicity. This was not the primary objective and there would have been insufficient power. It has been suggested that the prevalence of cam morphology differs within different ethnicities, with a lower prevalence found in Asian subjects.^{108,112,120,128} In this study there were equal numbers of White subjects in the sample compared to the general population. However there was over representation in the study sample of 'other ethnic groups' (7.2% versus 1%) and under representation of 'Black/ African/ Caribbean/ Black British' (0.6% versus 3.3%) and 'Asian' groups (5.5% versus 7.5%). It is difficult to know how this may impact the prevalence estimates, and whether this is actually a reflection of the local population served by the major trauma centre. A further study would be necessary to specifically examine if ethnicity affects prevalence of cam and pincer morphology.

I assessed the risk of bias in this study using the same criteria that I used in chapter 2. I believe this study has a low risk of bias in 8 categories. I rated it as a high risk in category 2 (was the sampling frame a true or close representation of the target population?) and category 3 (Was some form of random selection used to select the sample, OR, was a census undertaken?). Overall I scored the study as having a moderate risk of bias.¹⁰¹

As I sampled different age groups up to 65 years it was expected that some patients, particularly in the older age groups, would have radiographic evidence of hip OA.²¹⁹ In osteoarthritic hips osteophytes form at the femoral head neck junction and around the acetabular rim.²²⁰ Therefore, the α angles and SEAs will be higher, potentially creating false positives. I therefore provided a sub group prevalence estimate that excluded cases of established osteoarthritis. This did reduce the

prevalence estimate of cam morphology to 35% (males 44% females 26%) and pincer morphology 47% of subjects (males 52% females 42%).

This sub-group estimate is similar to the prevalence reported by Hack et al, which was used to inform the sample size calculation.⁹⁴ Hack et al reported a prevalence of cam morphology of 34%, although there sources of bias in their sampling (see chapter 2).⁹⁴ Other studies that defined the presence of cam using cross sectional imaging include Omoumi et al.¹²⁵ They report a prevalence of 61% when assessing α angles greater than 55° at 1:30 o'clock.¹²⁵ While Kang et al report a prevalence of cam morphology of just 12% when measuring α angles greater than 55° at 3 o'clock.¹²⁴

Comparing this prevalence estimate of pincer morphology to other studies is challenging given the different methods used to define its presence. Compared to other studies utilising cross sectional imaging this prevalence estimate for pincer morphology appears high. This was anticipated given the weak diagnostic performance of the test. It justifies not drawing conclusions based on the point prevalence of pincer morphology defined by the criteria developed in chapter 4. Kang et al report a prevalence of subjects with an acetabular anteversion less than 15° of 16% and a CEA greater than 40° of 18%.¹²⁴ Omoumi et al report the prevalence of a CEA greater than 40° to be 16%.¹²⁵

The number of patients assessed in this study is modest compared to other studies of the prevalence of cam and pincer morphology.^{103,105,135} The number of subjects may have been greater in the studies by Agricola et al, Gosvig et al and Laborie et al, but their studies were limited in that they only assessed plain radiographs. As demonstrated in chapter 4 and by Rakhra et al single measurements of cam and pincer morphology, such as plain radiographs, lack sensitivity to detect cam and pincer morphology.¹³⁸ The limiting factor in this study, that prevented me assessing more subjects, was the time constraints to manually assess each subject's CT. It would not have been feasible to assess the large numbers of subjects that Agricola et al, Gosvig et al and Laborie et al have. However, my sample size calculation showed

that assessing 200 subjects could estimate the prevalence to a confidence interval width of 0.1; which it was in this study.

The results of this study raise concerns over the diagnosis and treatment of FAI syndrome. The diagnostic criteria used were those developed in chapter 4. These criteria represented those patients whom surgeons had diagnosed with FAI syndrome and who were offering hip arthroscopy and reshaping surgery. This study demonstrated that a high proportion of the general population have similar hip morphology. It is reported that only 4% of young adults report hip pain.²²¹ Many asymptomatic subjects will have cam or pincer morphology. Is it correct to change the shape of those patients with the same morphology, who suffer hip pain and have certain, ill defined, clinical signs?^{153,156,162,222,223} This point is compounded by the view that the numbers of patients undergoing hip arthroscopy for FAI syndrome has increased significantly over the last decade, a diagnosis and treatment that was not previously available.⁵⁻⁷ It raises the possibility that FAI syndrome is being over diagnosed or over treated with arthroscopic surgery, and so the diagnostic criteria I determined in chapter 4 were overly sensitive and insufficiently specific.

Strengths of this study are that the sampling frame included equal numbers of men and women of different ages and that the definition of cam and pincer morphology had a defined diagnostic utility. The use of CT scans that allow a three-dimension assessment of hip shape is also a strength of this study as it offers an improved sensitivity for disease. Weaknesses include the retrospective study design, which prevented the collection of data on the presence of hip pain and examination findings. This data would have allowed me to report if any subjects in the sample fulfilled the criteria to diagnose FAI syndrome and also to determine if there is an association between hip pain and hip morphology. A further weakness relates to the definitions used to define cam and pincer morphology. These were discussed in length in the previous chapter. The prevalence estimate reported here can only be as accurate as the diagnostic criteria used.

In order to improve our understanding of the epidemiology of FAI syndrome prospective studies that assess the association between hip pain, clinical findings

and hip morphology are required; this would establish the prevalence of FAI syndrome in the population. While this study has attempted to establish a reliable estimate of the prevalence of cam in the general population there are suggestions that it may be different in certain athletic sub groups.^{130,134} Using the case definitions developed in chapter 4 I hope to assess this in chapter 6.

5.6 Conclusion

In a sample broadly representative of the UK general population, using the criteria developed in chapter 4, cam morphology was identified in 41% of participants aged 16-65 (males 51% and females 30%). When excluding subjects with radiographic hip OA this estimate reduced to 35% of subjects (males 44% females 26%).

5.7 Reflections

In this chapter, I intended to define the point prevalence of cam and pincer morphology in the general population. I was able to use a convenience sample that was broadly representative of the population and apply the definitions for cam and pincer morphology established in the previous chapter. This chapter offered me the opportunity to produce some original research, putting into practice the lessons I had learnt in the previous chapters.

I was surprised that the prevalence estimates of cam and pincer morphology were so high. My interpretation of this result is that there are significant numbers of subjects in the general population who have a similar hip shape to those patients that surgeons would consider offering shape-changing surgery (although in the absence of symptoms and clinical signs). This does raise the possibility of over diagnosis and over treatment. If overtreatment is occurring, how do we change practice?

It is hard to know if over diagnosis and overtreatment of FAI syndrome has always been the case. It is possible that an evolution has occurred over time, as the surgical technique of shape changing surgery became more established. However, it is difficult

to measure this potential change retrospectively. In order to prevent such a problem a true understanding of the epidemiology is required. The relationship between different hip shapes and the consequent development of symptoms (FAI syndrome) is poorly understood. Epidemiological studies that observe subjects, with a known hip morphology, over time, would help to delineate the relationship between cam and pincer morphology and FAI syndrome and the development of hip OA. Conducting this type of cohort study in an era where the diagnosis is increasingly recognised and where patients will seek treatment once diagnosed could be problematic. The desire for treatment makes understanding whether symptoms are self limiting or likely to resolve more difficult. I believe there are alternative study designs that may help address these research questions.

- 1) A RCT of active arthroscopic surgery with appropriate reshaping versus placebo surgery for patients with FAI syndrome.*

This study design would establish the role of shape changing surgery in patients with FAI syndrome by assessing patient reported outcomes measures. Using secondary outcomes that assessed changes in the risk of hip OA would also demonstrate if altering the hip shape changes the risk of hip OA. Two placebo controlled RCTs are being conducted, the FIRST trial in Canada (NCT01623843) and HIPARTI trial in Finland (NCT02692807). These studies are assessing patient reported outcomes only.

- 2) A retrospective analysis of a historical cohort study, that was inception prior to the description of FAI syndrome to determine the prevalence of FAI syndrome and observe subjects requirements for hip arthroplasty over time.*

This study will help distinguish between the natural history of subject with FAI syndrome and those with isolated cam morphology. I am aware of a cohort study which may have sufficient quality data. The Somerset and Avon Survey of Health (SASH) was designed to assess the future requirements of hip and knee arthroplasty in the UK.²²⁴ It began in 1994 and sampled 26,000 subjects in Bristol and Somerset region. Subjects completed detailed questionnaires, following which a selection of subjects underwent a comprehensive clinical examination and radiographic examination. I am presently exploring the feasibility of using this study to determine the point prevalence of FAI syndrome and the natural history of the disorder.

In order to reduce the possibility of over diagnosis and over treatment of FAI syndrome I believe we need to improve our understanding of the natural history of cam and pincer hip shapes. Only when we truly understand the epidemiology of FAI syndrome will we be able to select subjects for the appropriate treatment.

6 Prevalence of Cam Morphology in Elite Golfers

In this chapter I assess a group of elite golfers and report the prevalence of hip pain, cam and pincer morphology and the association between hip morphology and hip pain.

Declarations

I received the following help in writing this chapter:

M Fernandez and I Ahmed helped collect questionnaire and clinical examination data.

P Robinson, R Cambell, P O'Connor selected the MRI protocols and provided a radiologistis report of MRI scans.

This work has been published:

Dickenson E, Ahmed I, Fernandez M, O'Connor P, Robinson P, Campbell R, Murray A, Warner M, Hutchinson C, Hawkes R and Griffin DR. Professional golfers' hips: prevalence and predictors of hip pain with clinical and MR examinations. *British Journal of Sports Medicine* 50.17 (2016): 1087-1091.

Dickenson E, O'Connor P, Robinson P, Campbell R, Ahmed I, Fernandez M, Murray A, Hutchinson C, Hawkes R and Griffin DR. Hip morphology in elite golfers: asymmetry between lead and trail hips. *British Journal of Sports Medicine* 50.17 (2016): 1081-1086.

This chapter has been presented at a national conference:

Title: Hip morphology in elite golfers: asymmetry between lead and trail hips

Presenter: E Dickenson Metting: British Association of Sports and Exercise Medicine Annual Scientific Meeting December 2015

Title: Professional golfers' hips: prevalence and predictors of hip pain with clinical and MR examinations.

Presenter: E Dickenson Meeting: British Association of Sports and Exercise Medicine Annual Scientific Meeting December 2015

This study was sponsored by the University of Warwick. University of Warwick Biomedical Sciences Research Ethics Committee approval was obtained for this study 16/6/15.

This work was funded by research grants received from Orthopaedic Research UK and British Society of Skeletal Radiologists.

6.1 Introduction

In chapter 2 I identified a number of studies that reported that the prevalence of cam morphology was higher in groups of professional athletes than the general population.^{33,82,96,97,130-134} Many groups of athletes have been well studied, such as footballers, where the prevalence of cam has been compared to a control population using the same methods, and reported to be higher.^{96,130} I was interested in assessing a previously unstudied group of professional athletes, with unique patterns of hip loading. I was interested in comparing their prevalence of cam and pincer morphology, with the general population.

Golf is one of the most popular sports globally with an estimated 57 million participants worldwide and 4 million in the UK.²²⁵ In 2016 golfers competed at the Rio de Janeiro Olympic games.²²⁶ In order to generate power in an efficient golf swing rapid hip rotation is required. The lead hip (left hip in a right handed player) moves rapidly, with a peak velocity of 228°/sec, from external rotation at the end of the back swing, to maximum internal rotation at the end of the down swing.²²⁷ Conversely the trail hip (right hip in a right handed player) rapidly rotates from internal rotation to external rotation with a peak velocity of 145°/sec.²²⁷ These rapid movements from extremes of hip rotation raise the prospect that golfers may be a group particularly susceptible to FAI syndrome due to the repetitive extremes of rotational hip movement.^{70,227} In theory the presence of cam or pincer morphology in golfers has the ability to negatively affect performance. Cam or pincer morphology may limit hip internal rotation, which is required in an efficient golf swing. Their presence may also contribute to intra-articular damage, causing pain.²²⁸

Some professional sportsmen have developed a joint morphology that is advantageous to their activity; for example increased humeral retroversion in the throwing arm of baseball pitchers, allowing greater external rotation at the glenohumeral joint.²²⁹⁻²³¹ To date no study has examined golfers' hip morphology, including the presence of asymmetry, and the impact this may have on associated symptoms.

6.2 Objectives

- Determine the prevalence of hip pain in elite golfers
- Determine the prevalence of cam morphology in elite golfers
- Report the population distribution of mean alpha angles between 12 and 3 o'clock, SEA at 2 o'clock and femoral antetorsion.
- Assess symmetry of hip morphology in elite golfers.
- Assess the association between hip shape and hip pain in elite golfers.

6.3 Methods

This is a cross-sectional clinical and radiological study of the hips in elite golfers.

After institutional ethical approval (University of Warwick Biomedical and Scientific Research Ethics Committee 16/6/15) I attended the attended the Scottish Hydro Challenge in Aviemore Scotland with a team of researchers. The Scottish Hydro Challenge is a European Challenge Tournament (the second tier men's professional golf tour in Europe). The research conducted at this event was part of a wider collaboration between University of Warwick, University of Southampton and the European Golf tour. I was the lead researcher for this collaboration. I shall present the findings of data that I collected, with the assistance of junior colleagues from the University of Warwick (MF and IA), and that I alone analysed.

6.3.1 Population

All golfers registering for the tournament (n=156) were invited to participate.

6.3.2 Participant Assessment

Questionnaires

Questionnaires determined player demographics including age, height, mass, years playing golf, hours of practice per week and any past history of hip injuries. The presence of hip pain was determined by asking players: 'In the past month have you had any pain in the hip or groin lasting one day or longer?'²²² Where players answered 'yes', they were asked which hip was affected. Players' hip related quality of life was determined, for each hip, using the international hip outcomes tool 12 (iHOT12), a validated tool for use in assessing young adult hips.^{232,233} The iHOT12 provides a score from 0-100, with 100 being the maximum; it is sensitive to change and does not show a ceiling effect. Subjects requiring surgery for a range of hip pathologies have been shown to have a mean score of 66 (SD 19.3), the minimal clinically important difference is 6.1 points.²³²

Physical Examination

Standardised physical examinations were undertaken by one of three orthopaedic surgeons (IA, MF and ED). We assessed passive hip flexion and abduction, with the players supine, using a handheld long arm goniometer with the end point determined as the point at which movement ceased or the pelvis moved.²³⁴ Hip internal rotation at 90° of flexion (IR90) was determined with the players seated using an electronic goniometer aligned to the medial aspect of the tibial crest using the technique described by Reichenbach et al.²³⁵ This technique uses weights and pulleys to apply a consistent force moving the joint into internal rotation. It has been demonstrated to have an improved inter-observer reliability compared to conventional methods of assessing the range of internal rotation.²³⁵ Flexion adduction internal rotation (FADIR) and flexion abduction external rotation (FABER) impingement tests were also undertaken.²³⁴ Impingement tests were considered positive if they elucidated hip or groin pain.²³⁴

Magnetic Resonance Examination

A portable 1.5 tesla (T) MR scanner (Siemens, Erlangen, Germany) was used to assess players' hip morphology. All players who completed questionnaires and physical examinations were invited to undergo an MR scan. Players who agreed to undergo MR examination were allocated appointment times on a first come basis, with the researchers blinded to the results of their questionnaires and physical examinations. MRI was conducted with participants supine and feet held together in neutral rotation with ties.

The following MR sequences were used: an axial fast spoiled gradient echo fat saturated 3D sequence from the anterior superior iliac spine to the lesser trochanters to assess hip morphology (Field of view 34cm, echo time (TE) 2.7ms, relaxation time (TR) 7.9ms, slice thickness 2mm, flip angle 0). A coronal and sagittal proton density fat saturated (TE 44.4, TR 2000, slice thickness 3mm) sequences of each hip were additionally used to assess intra articular pathology. In order to assess femoral antetorsion, the axis of the femoral condyles was determined using a localiser sequence (TE 1.3, TR 4.9, slice thickness 3mm).

6.3.3 Image Analysis

MR 3D volume sequences were reconstructed using Osirix DICOM viewer (version 8 32 bit) to assess hip morphology.¹⁹¹

Cam Morphology

Femoral neck morphology was assessed by measuring α angles around the axis of the femoral neck at 30° intervals as described in chapter 4.⁶² The population distribution of the mean α angle between 12 and 3 o'clock for lead and trail hips was reported. Cam morphology defined as a mean α angle between 12 and 3 o'clock greater than 52°.

Acetabular Morphology

Acetabular morphology was assessed by measuring the SEA around the axis of the acetabulum, as described in chapter 4. The population distribution of the SEA at 2 o'clock for lead and trail hips was reported. Pincer morphology was defined as a SEA measured at 2 o'clock than was greater than 80.5°. Given the poor diagnostic utility of this measure conclusions on the point prevalence of pincer morphology were not drawn.

Femoral Neck Antetorsion

Femoral neck antetorsion was measured on axial slices of the hip, using slices through the posterior condyles of the knee as a reference.¹⁹⁹ The population distribution of femoral neck antetorsion for lead and trail hips was reported. Femoral neck antetorsion of less than 0° was defined as femoral neck retrotorsion.

6.3.4 Statistical Analysis

Summary statistics were used to describe baseline player demographics and differences in player reported pain, iHOT12 scores, hip range of motion, α angles, SEAs and femoral neck antetorsion between the lead and trail hips. Hips were referred to as lead (left hip in a right and trail hip) and trail (right hip in a right handed player). Differences in the baseline demographics of the groups who completed questionnaires only, questionnaires and physical examination and questionnaires, physical and MR examinations were compared using Chi squared, independent T tests and Mann-Whitney test depending on the data type and distribution. Differences in the presence of pain between the lead and trail hips were assessed with a Chi squared test. Wilcoxon signed rank test and paired T tests were used to assess differences between lead and trail hips for parametric and non-parametric data respectively with an α value of 0.05. As 12 separate measures of α angle and SEA were made on each hip a Bonferonni correction was applied giving an α value of 0.004.²³⁶ Following examinations of the individual variables and the relationships between variables, a stepwise multiple linear regression was conducted. This was used to assess the relationship between iHOT12 scores and the mean α angles between 12-3 o'clock, femoral antetorsion, SEA at 2 o'clock, BMI, age

and practice time. The model was tested to ensure it did not violate the assumptions of linearity of residuals, multicollinearity and homoscedacity. An estimate of the prevalence of FAI syndrome was made by the number of players who reported hip pain, had positive impingement signs and evidence of cam or pincer morphology. These factors satisfy the criteria to diagnose FAI syndrome defined in chapter 3. Statistical analysis was conducted using SPSS statistics v22 (IBM, Armonk, USA).

6.4 Results

The Scottish Hydro Challenge was attended by 156 professional male golfers, 109 competitors (70% of the field) completed questionnaires, 73 (47% of the field) completed questionnaire and underwent physical examination and 55 (35% of the field) completed questionnaires and underwent physical and MR examination (see Figure 39). Six players were left handed (right hip lead hip) while 103 were right handed (left hip lead hip).

Figure 39 Participants assessed

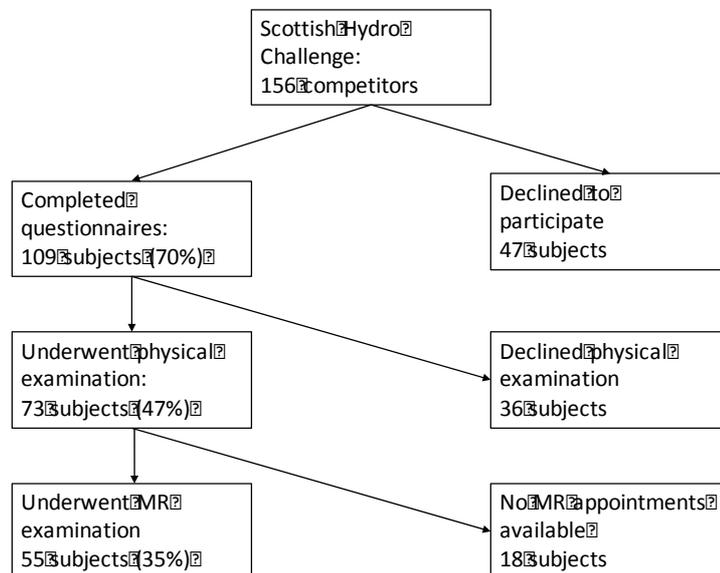


Table 27 Player Demographics

	Questionnaire only	Questionnaire vs physical exam p=	Questionnaire and Physical Examination	Physical exam vs MR exam p=	Questionnaire, physical and MR Examination	Questionnaire vs MR exam p=
n=	109	n/a	73	n/a	55	n/a
Mean age years	29 (+/- 6)	0.217	30 (+/- 6)	0.808	28 (+/- 6)	0.210
Mean years playing golf	19 (+/-6.6)	0.034	21 (+/- 6.0)	0.286	20 (+/- 6)	0.385
Mean hours of practice/ week	38 (+/-12.0)	0.597	38 (+/-12.0)	0.385	39 (+/-11.9)	0.717
Height /cm	182 (+/-6)	0.876	182 (+/- 6)	0.661	182.5 (+/- 5.8)	0.778
Mass/ kg	82 (+/-10)	0.502	83 (+/- 10)	0.753	82.3 (+/- 9.4)	0.735
Mean BMI	24.6 (+/-2.6)	0.990	24.6 (+/- 3.9)	0.909	24.7 (+/- 2.4)	0.911
Self report hip pain	21 (19.3%)	0.554	16 (22%)	0.425	13 (24%)	0.818
Median iHOT12 (IQR)	95 (88-99)	<0.001	89 (81-94)	<0.001	93 (86-97)	0.073

6.4.1 Questionnaires

Baseline player demographics are reported in Table 27. Twenty-one players (19.3%) complained of hip or groin pain lasting one day or longer over the preceding month. The lead hip/ groin was painful in 14 (11.9%) and the trail hip/ groin in 9 (9.1%) players (p=0.378). The median iHOT12 scores for the lead hip was 94 (IQR 86-98) compared to the trail hip 95 (IQR 90-99) (p=0.007) meaning the hip related quality of life was *statistically* lower for the lead hip compared to the trail.

6.4.2 Physical Examinations

The players who underwent questionnaire and physical examination had lower median iHOT12 compared to the questionnaire group (95 vs 89) (p<0.001), the difference in the self reported hip pain was 19 versus 22% (p=0.55); see Table 27. The examination findings are summarised in Table 28. There were no statistically significant differences in examination findings between the lead and trail hips.

Table 28 Physical Examination Findings

	Lead hip (n=73)	Trail hip (n=73)	p=
Flexion/° (SD)	101 (6.5)	101 (6.7)	0.426
Abduction/° (SD)	43 (9.1)	43 (8.1)	0.666
IR90/° (SD)	32 (6.2)	31 (6.7)	0.442
Number of positive FADIR tests (%)	15 (20.5)	15 (20.5)	1
Number of positive FABER tests (%)	9 (12.3)	7 (9.6)	0.596

6.4.3 MR Examinations

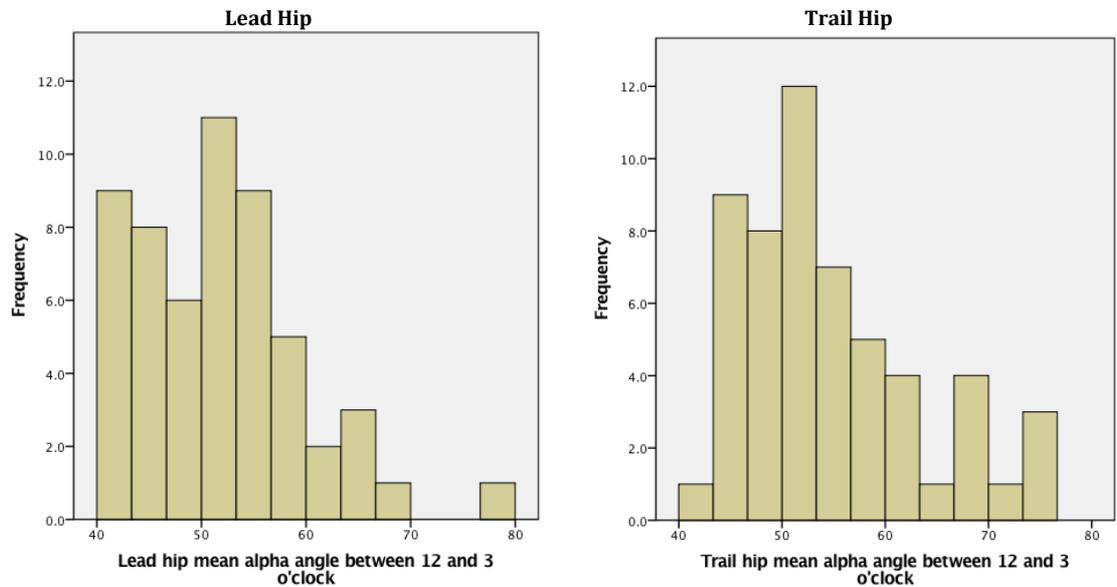
The players who underwent questionnaire, physical and MR examination had a median iHOT12 score of 93; see Table 27. This was statistically higher than questionnaire and physical examination group ($p < 0.001$) but not different to the questionnaire group ($p = 0.073$). There were no other statistically significant differences between the questionnaire, physical and MR examination group and the other groups.

Cam Morphology

The difference between lead and trail hip α angles reached statistical significance at 2 and 3 o'clock (see Table 29) with lower α angles in the lead hip. The population distribution for mean alpha angles measured between 12 and 3 o'clock for lead and trail hips is shown in Figure 40.

Cam morphology was present in 33 players (60% 95%CI 47-73) and 51 hips (46% 95%CI 37-56). Both hips were affected in 18 players; the lead hip was affected in isolation in 4 players and the trail hip in isolation in 11 players ($p = 0.071$).

Figure 40 The population distribution for mean alpha angles measured between 12 and 3 o'clock for lead and trail hips

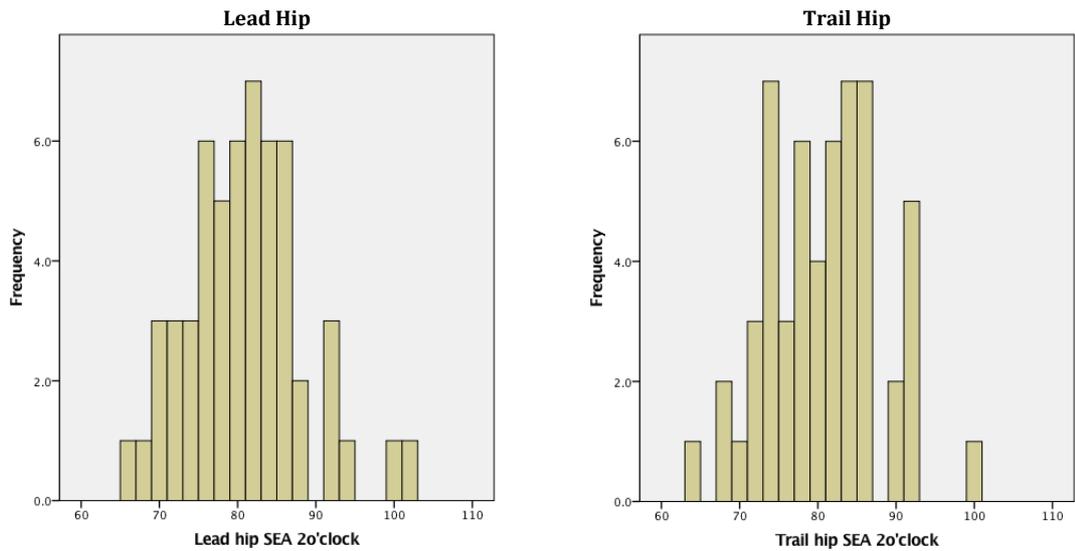


Pincer Morphology

The difference in the SEA at different positions on the acetabulum between lead and trail hips are shown in Table 30. At no position did the difference reach statistical significance. The distribution of SEAs measured at 2 o'clock for lead and trail hips is displayed in Figure 41.

Pincer morphology was present in 34 players (62% 95%CI 49-74) and 55 hips (50% 95%CI 41-59), both hips were affected in 21 players, the lead hip was affected in isolation in 6 players and the trail hip affected in isolation in 7 players (p=1).

Figure 41 The distribution of SEAs measured at 2 o'clock for lead and trail hips



Femoral neck antetorsion

Mean femoral neck antetorsion was greater for lead hips at 16.7° (SD 7.5) compared to 13.0° (SD 7.2) in trail hips (p<0.001). The distribution of antetorsion for lead and trail hips is displayed in Figure 42.

Femoral retrotorsion was present in 2 players (3.6% 95%CI 1-12) with the trail hip affected in isolation in both cases (p=0.157).

Figure 42 The distribution of antetorsion for lead and trail hips

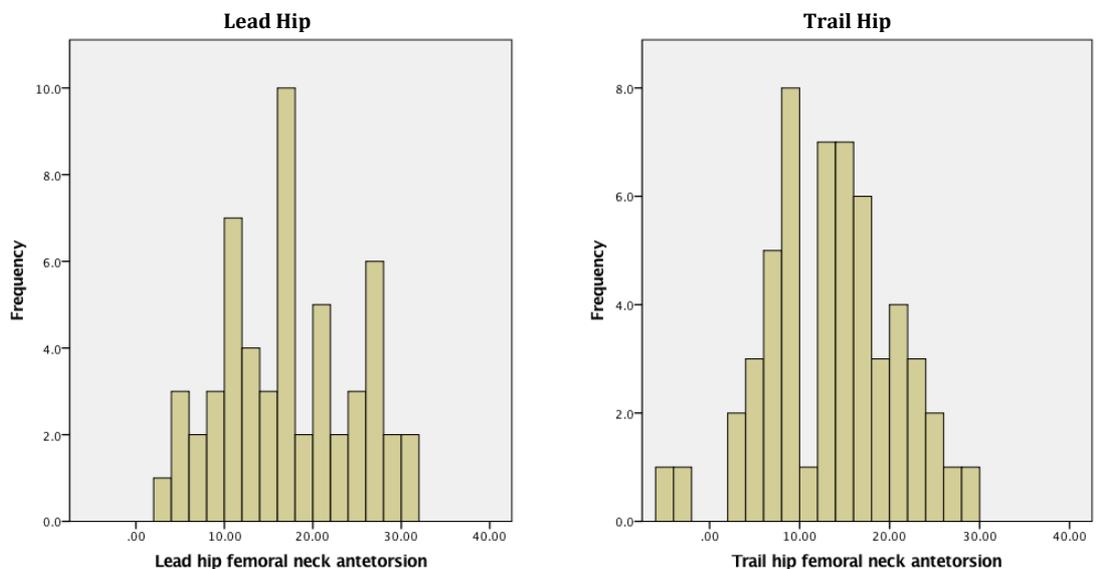


Table 29 Proximal Femoral Morphology

	α angle/ ° (Inter Quartile Range)											
Position on femoral neck (o'clock)	12	1	2	3	4	5	6	7	8	9	10	11
Trail hip median	45 (42-49)	66 (55-80)	56 (48-68)	45 (40-52)	40 (37-44)	42 (40-44)	43 (41-45)	38 (36-41)	36 (36-38)	39 (36-42)	42 (39-45)	41 (39-42)
Lead hip Median	46 (44-48)	62 (52-73)	51 (46-57)	41 (38-46)	39 (37-43)	43 (40-45)	44 (42-46)	39 (37-43)	37 (35-40)	39 (36-42)	40 (38-43)	39 (38-42)
p value	0.661	0.053	<0.001	0.001	0.885	0.094	0.006	0.069	0.027	0.584	0.016	0.075

Table 30 Acetabular Morphology assessed by Subtended edge angles

	SEA/ ° (Inter Quartile Range)											
Position on acetabular axis (o'clock)	12	1	2	3	4	5	6	7	8	9	10	11
Trail hip median	78 (76-82)	83 (78-87)	81 (74-85)	76.0 (72-81)	86 (82-90)	83 (78-87)	82 (77-90)	95 (92-99)	89 (86-94)	78 (74-84)	71 (68-76)	71 (68-76)
Lead hip median	78 (73-81)	82 (79-88)	80 (76-85)	77 (70-83)	85 (82-89)	82 (78-87)	81 (82-86)	93 (91-98)	89 (84-93)	78 (73-82)	72 (66-78)	71 (67-75)
p value	0.004	0.570	0.647	0.176	0.739	0.414	0.245	0.012	0.065	0.181	0.625	0.043

6.4.4 Associations with hip pain

A stepwise multiple linear regression was used to predict the relationship between iHOT12 scores and the mean α angles between 12-3 o'clock, femoral antetorsion, SEA at 2 o'clock, BMI, age and practice time.

A multivariate regression model revealed an R^2 of 0.21 ($p < 0.001$) for a mean α angle between 12 and 3 o'clock ($\beta = -0.500$ $p < 0.001$) and for SEA at 2 o'clock ($\beta = -0.308$ $p = 0.014$) to be significant predictors for hip quality of life; see Table 31. This means that the model is able to predict 21% of the variance in iHOT12 scores.

Femoral neck antetorsion ($\beta = -0.007$ $p = 0.943$), BMI ($\beta = 0.38$ $p = 0.680$), practice time ($\beta = 0.012$ $p = 0.889$) and age ($\beta = -0.151$ $p = 0.123$) were not significant predictors.

Table 31 Multiple Linear Regression model of iHOT12 scores

Predictor	β coefficient	95% CI	p Value
Mean alpha angle 12-3 o'clock	-0.500	-0.713, -0.286	<0.001*
SEA at 2 o'clock	-0.308	-0.554, -0.062	0.014*
Age	-0.151	n/a	0.123
BMI	0.38	n/a	0.680
Practice time	0.012	n/a	0.889
Femoral neck antetorsion	-0.007	n/a	0.943
CI = confidence intervals *= significant values			

6.4.5 Prevalence of FAI syndrome

Of the 55 players who completed questionnaires, underwent physical and MR examinations six players (11%) including nine hips (8%) reported hip pain, had a positive FADIR or FABER impingement tests and had cam or pincer morphology present.

6.5 Discussion

In this study I have reported the prevalence of hip/ groin pain, cam and pincer morphology, femoral neck retrotorsion and the physical examination features of elite male golfers who attended the Scottish Hydro Challenge. This study was a cross sectional assessment of European elite male golfers.

In this group of elite golfers the point prevalence of self reported hip/ groin pain, using a tool developed for use in population studies, was 19.3%.²²² This figure seems high given the mean age of the sample was 29 years. Urwin et al reported the prevalence of hip pain lasting at least one week in the last month in males aged 16-45 years was 3%.²²³ Birrell et al, using the same method as described in this study, reported the prevalence of hip/ groin pain in males and females aged 18-80years was 10%.²²² Using either of these definitions it appears that golfers report more hip/ groin pain than the general population. A previous systematic review by Cabri et al assessing golfing injuries reported the prevalence of hip injuries was between 2 and 18%.²³⁷ It is unclear from this review how hip injuries were defined and if the included studies were homogenous. In professional tennis, where rapid hip rotation is also required, hip pain is reported in 8-27% of players compared to 19.3% of golfers in this study.²³⁸ Gosheger reports that professional golfer on average play at least four rounds of 18 holes and hit at least 200 ball on the driving range per week.²³⁹ Given the repetitive nature and the forces involved during a swing it isn't surprising that golfers report a higher degree of hip/ groin pain than non golfers.^{227,239} This may go some way to explain the reported point prevalence of hip injuries in golfers of between 2 and 18%.²³⁷

There was no difference in rates of self-reported hip/ groin pain (a binary measure) between lead and trail hips. However there were statistical differences in the iHOT12 (a continuous variable), between the lead and trail hip with lower scores for lead hips. I had anticipated that there might be more hip pain reported in the lead hip given the rotational forces are greater and that at the end of the downswing the lead hip ends in a position association with FAI syndrome.²²⁷ These statistical differences in the iHOT12 must be set in the context of the score. The iHOT12 has a

minimally clinically important difference of 6.1 points, the difference in the median values between lead and trail hips was only 1 (lead hip 94, IQR 86-98, versus trail hip 95, IQR 90-99).^{232,233} This statistical difference appears not to have a clinical relevance.

The group of players that underwent questionnaire and physical examination had statistically lower iHOT12 scores compared to the group that completed questionnaires only. In all other demographics there were no statistical differences between groups, including self-reported hip pain. I was concerned when planning this research that a non response bias would be introduced with players who had not suffered hip pain less motivated to participate. The distinction in the iHOT12 scores between the group who completed questionnaires and those who consented to questionnaire and physical examination does suggest this bias was present. The difference in the median iHOT12 between the questionnaire and physical exam and questionnaire only group was 6 (89 vs 95); this is in the order of the minimally clinically important difference of the iHOT12 (6.1).²³² It was reassuring that no such differences occurred between the questionnaire only group and the questionnaire, physical and MR examination group. However, there is a diluting effect of comparing the same subjects data. A subject who underwent questionnaire, physical and MR examination will be represented in the between group comparisons in Table 27 in the questionnaire data, questionnaire and physical examination, and questionnaire, physical and MR examination groups. The value of these between group comparisons in demonstrating a limited non-response bias is questionable. It was also reassuring that I was able to collect data on 70% of the players attending the competition. However the modified risk of bias tool for epidemiological studies reports that in order for a study to be rated as a low risk of bias, with respect to non responder bias, a response rate of greater than 75% of the sample is required.¹⁰¹

The physical examination findings were unremarkable, even in the context of subjects with different hip shapes and the asymmetrical nature of golf. The lack of a clinically detectable difference may be because differences, if they exist, lay within the standard error of the measurements or due to errors in the methods used to collect the data.^{234,235}

The prevalence of cam morphology in this population of golfers was 60% of players and 46% of hips. This compared to a prevalence of 51% of all males and 38% of all male hips in the general population reported in chapter 5. Despite the trends suggestive of a higher prevalence of cam morphology in golfers, there was insufficient evidence to dismiss the null hypothesis (Chi Squared test $p=0.187$). There was also no statistical significant difference between the mean α angles between 12 and 3 o'clock, (golfers 51.4 IQR47-58 versus general population 50.3 IQR45-56) or the SEA at 2 o'clock (golfers 81 IQR75-85 versus general population 81 IQR76-89), comparing elite golfers and the general male population (Mann-Whitney U test alpha angles $p=0.077$ SEA $p=0.077$). However, this may represent a type 2 error given the large number of subjects that would be required to detect a relatively small difference in α angles, SEAs and prevalence rates.

In the antero-superior portion of the femoral head neck junction (1-3 o'clock), where cam morphology is most frequently identified,¹³⁸ median α angles were higher in the trail hips (66, 56 and 45 versus 62, 51, and 41°) reaching statistical significant at 2 and 3 o'clock. Other studies assessing hip morphology in athletes have not demonstrated differences in proximal femoral morphology between hips.^{33,96,97,130,132-134} In the general population, Hack et al measured α angles in the hips of 200 volunteers. Although not tested for statistical significance, Hack reported a slight difference in the α angles of the left and right hips (left: 40.6 [95%CI 39.6-41.6] and 50.1 [48.9-51.2] versus right 40.9 [39.9-41.9] and 50.2° [49.1-51.4] at 1:30 and 3o'clock respectively).⁹⁴ These differences were far smaller in magnitude than those reported in this study.

Femoral neck antetorsion was statistically higher in the lead, compared to trail hips. The clinical significance of this finding is questionable given the magnitude of the difference and as previous studies have demonstrated a similar phenomenon within the general population.⁴⁶ Sutter et al found that asymptomatic volunteers had 14.8° of left hip antetorsion compared to 11.0° in the right hip.⁴⁶

The differences described in lead and trail hip morphology in golfers represent an interesting phenomenon. Golfers require rapid lead hip internal rotation during the golf swing. Theoretically reduced α angles and greater femoral neck antetorsion should increase the ability of the hip to internal rotate, which could translate into a competitive advantage in elite golfers.^{46,53} However, I found no difference in rotational range of motion between hips. Despite no clinically detectable difference in the rotational range of motion between hips, the presence of these morphologies does appear to be associated with a reduced incidence of lead hip intra articular soft tissue injuries. Data assessed by my collaborators (PR, POC, RC), that we have published, showed that the presence of labral tears and cartilage delamination was more frequently observed in trail hips.^{32,46,240} This finding contrasts with the increased prevalence of lead hip pain reported in this study. Tears to the labrum are considered to be a source of hip joint pain.²⁴¹ However the instruments used to assess hip/ groin pain used in this study may have been insufficiently specific to distinguish different causes of groin pain (e.g. hip related from adductor or inguinal related).¹⁸⁴ There may be other causes of hip or groin pain in the lead hip, or the increased load during the golf swing may contribute to the increased reporting of lead hip/ groin symptoms.

What remains to be established is whether the observed unique hip morphology of golfers develops in response to a certain pattern of loading and asymmetrical movements or whether the asymmetry is due to elite golfers being self-selected as individuals with these characteristics. It has been suggested that cam morphology develops in response to vigorous loading of the hip during adolescence.^{85,86} The differences in the shape of the head neck junction between golfers' lead and trail hips (lower α angles in antero-superior portion of lead hip) adds weight to the concept that cam morphology develops prior to skeletal maturity in response to certain loading patterns, if we assume elite golfers were regularly playing as adolescence. Trail hips in golfers have an external rotation moment as golfers' swing.²²⁷ Roels et al used finite element models to demonstrate that increased external rotation of the hip during adolescence stresses the antero-superior portion of the femoral neck; promoting bone formation in the area that corresponds to where cam morphology is identified.⁸⁷

Similar differences in bony morphology that are potentially advantageous within a sport have been demonstrated in baseball pitchers. Several studies have shown pitchers' develop greater humeral head retroversion compared to their non-throwing arms and control subjects.²²⁹⁻²³¹ This adaptation is believed to allow faster bowling. These studies hypothesised that this was the result of a bony adaptation to the sport, although I am not aware of any prospective studies that observed subjects through development.²²⁹⁻²³¹ With respect to femoral neck antetorsion in golfers, it is plausible that a similar mechanism occurs where the reduction in antetorsion that occurs during growth, is less marked in lead hips, in response to repetitive golf swings,^{231,242} However the differences of antetorsion between hips found in this study were similar to those identified in one study of the general population.⁴⁶ Longitudinal studies assessing adolescent golfers and controls would be required to demonstrate this.

This study predicts 21% of the variance of the hip related quality of life scores in golfers, with increasing mean α angles between 12 and 3 o'clock and increasing SEA at 2 o'clock proving significant predictors of a lower score. These associations may be the result of premature contact of the femoral neck and acetabulum during the golf swing.⁴ The presence of cam morphology was also found to predict groin pain in capoeira competitors.¹³³ However three other studies of athletes and the general population found no correlation between hip pain/ hip related quality of life and cam morphology.^{123,135,243}

In this study I report the number of golfers who fulfilled the criteria used to diagnose FAI syndrome; hip pain, positive impingement tests and the presence of associated morphologies (e.g. cam or pincer). Based on this definition the point prevalence of FAI syndrome in golfers is 11% (8% of hips); this estimate must be taken with extreme caution, as these subjects were not diagnosed with FAI syndrome; they simply fulfilled certain diagnostic criteria. The reporting of pain was not necessarily pain that was hip joint in origin, the clinical examination failed to identify or suggest alternative causes of hip pain, and the impingement signs (used to define positive examination findings) are known to be sensitive without

specificity and offer little consistency between examiners.^{8,156,169} Unfortunately no other studies have reported the prevalence of FAI syndrome in order to set this result in context. It is likely to be an overestimate.

This study was designed as a cross sectional evaluation of elite golfers combining clinical and radiological assessments. I was only able to assess male elite golfers, as there were no females competitors at this event. The study occurred over a three-day period while golfers arrived and registered at the competition. During this period I was able to assess 109 out of 156 competitors. This limited sampling in itself is a source of non-response bias. Due to time constraints I was unable to better plan the samples that were examined and imaged; hence the non-response bias observed in the physical examination group. If I had been able to recruit and collect questionnaire data from subjects in advance I might have been able to conduct more robust sampling, and therefore have a truly representative sample of elite golfers undergoing physical examination and MR scans. However the non-response bias observed was in the subjects who completed physical examination compared to the questionnaire group and not the MR group compared to the questionnaire group. The lack of physical examination data was because players didn't consent; not because a timetabling issue. Even if I were able to better plan the sampling prior to the tournament it would still be dependent on the golfers complying with appointments. Something I observed that they were not good at, as they are an independently minded group. Although I failed to sample 75% of the field required in order to minimise the non-response bias I was pleased to achieve a sample of 70% of the entire field completing questionnaires. A professional golf tournament is a difficult setting to recruit research participants; competitors would rather play golf! Apart from some missed appointments on the first morning when not many players had arrived, the number of MR scans performed reached saturation; the MR scanner was unable to scan more subjects in the 3 day period we attended.

I did not set out, a priori, the numbers of golfers I wanted to assess in order to achieve my objectives; I viewed the sample as a convenience sample and sought to assess as many subjects as possible in the time period available. Therefore the comparisons I have made between golfers and the general population, and between

golfers hips may be subject to a type two error. In order to determine if a difference exists in the prevalence of cam and pincer morphology between the golfers and the general population (with a 90% power and an α value of 0.05), based on my reported prevalence estimates, 71 and 730 golfers respectively would be required. It could be the lack of a statistically significant difference in the prevalence of cam morphology between golfers and the general population was the result of a type two error.

6.6 Conclusion

In conclusion 19% of male golfers report hip pain, 60% have cam morphology and 62% have pincer morphology. There was statistically significant differences in the proximal femoral morphology of golfers lead and trail hips, with lead hips having lower α angles in the antero-superior region and greater femoral neck antetorsion. An increase in the mean α angle between 12-3 o'clock and SEA at 2 o'clock were associated with a reduced hip related quality of life.

6.7 Reflections

This original research was the culmination in a number of years work by my colleagues and I. Through this chapters reflections I discuss the preparatory work we conducted, as well as how I used training I've received during my degree to analyse the results and maximise the research's impact.

Prior to conducting this particular piece of research I had worked with colleagues to develop a method of swiftly assessing groups of athletes consistently with questionnaires, clinical examination and MR examination. In 2014 I attended the Scottish Hydro Challenge (same event as this study) with MF. At this time we were simply collecting preliminary questionnaire data to explore whether hip pain was a significant issue in golfers. We learnt practical ways to improve our success in sampling the players at this event, as well as a preliminary demonstration of the

significance of hip pain in golfers. Following this event I attended the England Golf annual meeting at St Georges Park in December 2014 with two other researchers. At this event we presented our findings from the Scottish Hydro Challenge and we were able to assess a group of semi professional golfers. We used this opportunity to perfect our ability to examine a large numbers of golfers in a short space of time.

In preparing the MRI protocols for this study I also had the opportunity to examine the England cricket team. I attended one of the elite squads medical screening events in Autumn 2014 where a mobile MRI scanner was booked, in order to assess the fast bowlers' spines. I was able to use this MRI scanner to image the cricketers' hips. For reasons of competitive sensitivity I have not published this data. As a cricket fan conducting this research was interesting on a personal level, however I cannot draw any scientific conclusions from such a small sample (n=16). I was able to report my findings regarding players I had particular concerns about to the chief medical officer and lead physiotherapist. This study on the England cricketers helped me establish what MRI protocols we could use in order to get the most information about golfers hips in a limited time. The results of this study are reported in the appendix section 11.3.

In planning this study I had the hypothesis that hip pain would be more prevalent in the lead hip of golfers, due to the greater rotational forces and the terminal position of the lead hip at the end of down swing. I had also intended to be able to describe the point prevalence of cam and pincer morphology. I had not anticipated that it would differ from the general population despite some evidence of an increased prevalence in cam morphology in other athletic groups. Conducting this study also provided me the opportunity to assess the relationship between hip shape and hip pain, something I failed to achieve in chapter 5.

When I completed my data collection and began to inspect the data I was genuinely surprised by the findings. I was observing what appeared to be differences in hip shape between the lead and trail hips. Following formal statistical testing I attempted to explain this unexpected finding. Baseball pitchers provided an opportunity to make comparisons to a well-studied group of athletes who also have large rotational

velocities, but in their glenohumeral joints. The finite element analysis that suggests external rotational moments on the hip promote the formation of cam morphology provided a mechanistic explanation of this finding.

Despite my preparatory work I personally wish I had assessed the reproducibility of the clinical examinations. If I were to repeat the study I would have spent more time ensuring the consistency of the examinations conducted by the team of researchers who attended this event. I should have undertaken more training before departing for the event and assessed the inter and intra-observer reliability of our findings at the event. Although figures for this are reported in the literature.^{234,235} My questions over the reliability of the examination data make me doubt the significance in the data differentiating lead and trail hip shapes. Ideally one person should have conducted all the physical examinations. However this was precluded by the time constraints during the golf tournament.

As well as some practical lessons about conducting research in this unique environment I also had to learn new research skills for my analysis. I do not believe I am naturally gifted in medical statistics and so conducting a multiple linear regression analysis was a challenge. I was able to augment my self-directed learning with a regression statistics course that I attended towards the end of my PhD. Luckily the analysis I had already conducted was robust.

Prior to publishing this research in the British Journal of Sports Medicine I had attended a university course as part of the postgraduate certificate in transferable skills. This course, "Science Communication", involved learning how to enhance your chances of your research being reported by journalists. One of the course faculty was a local BBC journalist and I talked to her about this study. She encouraged me to submit a press release (see appendix section 11.3) when the journal published the research, as she thought this would be of interest to the media. Fortunately the BJSM published my two papers in the same week as the Rio de Janeiro Olympics, when Justin Rose of Great Britain had just won the first gold medal in golf at an Olympic games. My corresponding press release was therefore topical and was picked up by several

journalists and reported in a number of mainstream news outlets including the BBC and the Daily Telegraph- see appendix section 11.3.

In summary, the research conducted in this chapter provided me the opportunity to develop a research hypothesis and test it. I was able to use research skills I acquired during my PhD training to design the study, conduct the analysis and disseminate the results. As with all research there are aspects that I would choose to do differently with hindsight, but overall I am proud of this piece of work.

7 Does cam and pincer morphology, or FAI syndrome cause hip osteoarthritis; a systematic review?

In this chapter I review the literature to assess whether there is causal relationship between femoroacetabular impingement syndrome and osteoarthritis of the hip.

7.1 Introduction

Since FAI syndrome was popularised by Ganz et al in 2003, it has been associated with hip osteoarthritis (OA).⁴ Ganz's description of FAI was titled "Femoroacetabular impingement: a cause for osteoarthritis of the hip" and other publications since have followed a similar pattern.^{4,32,244} But is there enough epidemiological evidence to state that FAI syndrome is a cause of hip OA or is there merely an association?

Proving true causality rather than an association is inherently difficult. In 1965 at the Royal Society of Medicine's Presidential address Professor Bradford Hill attempted to describe criteria that should be satisfied in order to determine causality of a disease.²⁴⁵ These have become known as the Bradford Hill criteria and consist of:

- Strength

Bradford-Hill described strength of the association as his first category in order to determine causality. He quotes the example of Percival Pott noting the mortality from scrotal cancer in chimney sweepers was 200 times that of the rest of the population or that lung cancer was 9-10 times more common in smokers than non smokers.²⁴⁵ In these examples the size of the effect was so large that it suggested a causal link. However, Bradford Hill does note caution, just because an effect may be relatively small, does not mean there is not causality. He uses the example of meningococcal septicemia, relatively few of us who are hosts of the bacteria go onto contract the disease, however there is a causal relationship.²⁴⁵

- Consistency

Bradford-Hill describes the need to display consistency in an observed association as a further evidence of causality. Was the same observed association ‘repeatedly observed in different populations, different places, circumstances and times?’²⁴⁵ In demonstrating consistency there needs to be a recognition that repeating the same methodologically flawed study and finding the same result is not the same as consistency of an effect between different study designs, even if some have inherent methodical flaws. Again, Bradford Hill notes caution in certain circumstances when repetition is absent or not possible that this should not prevent us drawing conclusions.

- Specificity

When one risk factor is present and disease always exists, it allows conclusions of causality to be drawn. This relationship is deemed to show specificity. However, there is no need for specificity in establishing causality.²⁴⁵ Bradford Hill uses the example of smoking and lung cancer. The lack of specificity (some non-smokers develop lung cancer) was long used as a reason to dismiss the causal link.

- Temporality

Bradford Hill described how in order to prove causality it is important to demonstrate that the risk factor came before the disease. Bradford Hill uses the examples of particular occupations and tuberculosis infection. ‘Does a particular occupation or occupational environment promote infection by the tubercle bacillus or are the men and women who select that kind of work more liable to contract tuberculosis whatever the environment’.²⁴⁵

- Biological Gradient

In order to satisfy this criteria there needs to be evidence of a dose response. For example as the amount of cigarette pack years increases so does the odds of developing lung cancer. Bradford Hill comments that demonstrating a biological gradient provides strong evidence of causality.

- Plausibility

It is helpful if the method of causation is biologically plausible.²⁴⁵ However, plausibility is not essential to demonstrate causality, as it only depends on the present day's understanding. An association that is new to medicine may not be biologically plausible, this does not mean it is not causal.

- Coherence

Coherence is described by Bradford-Hill as the cause and effect interpretation not conflicting with generally known facts about the natural history of disease. However, he does recognise that coherence is not an essential to determine a causal relationship. As evidence of coherence to the theories that smoking causes lung cancer, Bradford Hill uses the example that chemicals found within cigarette smoke are carcinogenic to the skin of animals.

- Experiment

Bradford-Hill described that experimental evidence provides the strongest support to theories of disease causality. He uses the example that reducing cigarette smoking alters the observed rate of lung cancer compared to subjects who do not reduce smoking. Since his 1965 presentation, randomised controlled trials have become the pinnacle of medical evidence.²⁴⁶⁻²⁴⁸

- Analogy

Bradford Hill states that in some circumstances it is acceptable to draw an analogy when attempting to determine causality. He uses the example of Rubella and thalidomide and their effects in pregnancy as an example that we would be willing to accept that other viral illnesses and drugs may cause neonatal abnormalities.

In this chapter I conduct a systematic review to evaluate the evidence to establish if FAI syndrome, cam or pincer morphology cause hip OA. The Bradford Hill criteria offer a useful standard to judge the evidence against. I therefore look for the literature to satisfy each Bradford Hill criteria.

7.2 Objectives

- To systematically review the available evidence that assesses the association (or causality) of cam morphology, pincer morphology or FAI syndrome with hip OA.

7.3 Methods

A systematic review was conducted in accordance with the PRISMA guidelines.¹⁰⁰

7.3.1 Types of Studies

All original studies that report the links between cam or pincer morphology, or FAI syndrome and hip OA were considered for inclusion. Studies not available in English language or as full text publications were excluded.

7.3.2 Types of Participants

Studies that included male and or female subjects of all ages were considered for inclusion.

7.3.3 Type of outcome measure

I assessed the evidence of causality according to the Bradford Hill criteria. Therefore a range outcome measures were accepted. For example to demonstrate *strength* odds ratios or relative risk were preferable, whereas to assess *plausibility or analogy* other presentations of outcome were acceptable; such as mechanistic descriptions. I did not plan a meta-analysis and therefore the mixture of outcomes would not compromise the results of the review.

7.3.4 Search Methods

Electronic Searches

Electronic searches were completed on 8/4/16 of MEDLINE (Medical Literature Analysis and Retrieval System Online) (1946-April 2016) and EMBASE (Excerpta Medica Database) (1980-April 2016). The following search terms “femoroacetabular impingement” or “FAI” or “hip impingement” or “cam” or “pincer” or “pistol grip deformity” and “osteoarthritis” or “hip osteoarthritis” were used. Searches were limited to human studies and English language.

7.3.5 Selection of Studies

I screened records by title, abstract and full text review to determine eligibility.

7.3.6 Data Analysis

Each eligible study was reviewed and it was determined which category(s) of the Bradford Hill criteria for causality they provided evidence to support. Each of the Bradford Hill criteria, and the studies deemed eligible within it, are reported in turn.

7.3.7 Risk of Bias Assessment

I assessed the risk of bias using the modified risk of bias tool for epidemiological studies.¹⁰¹

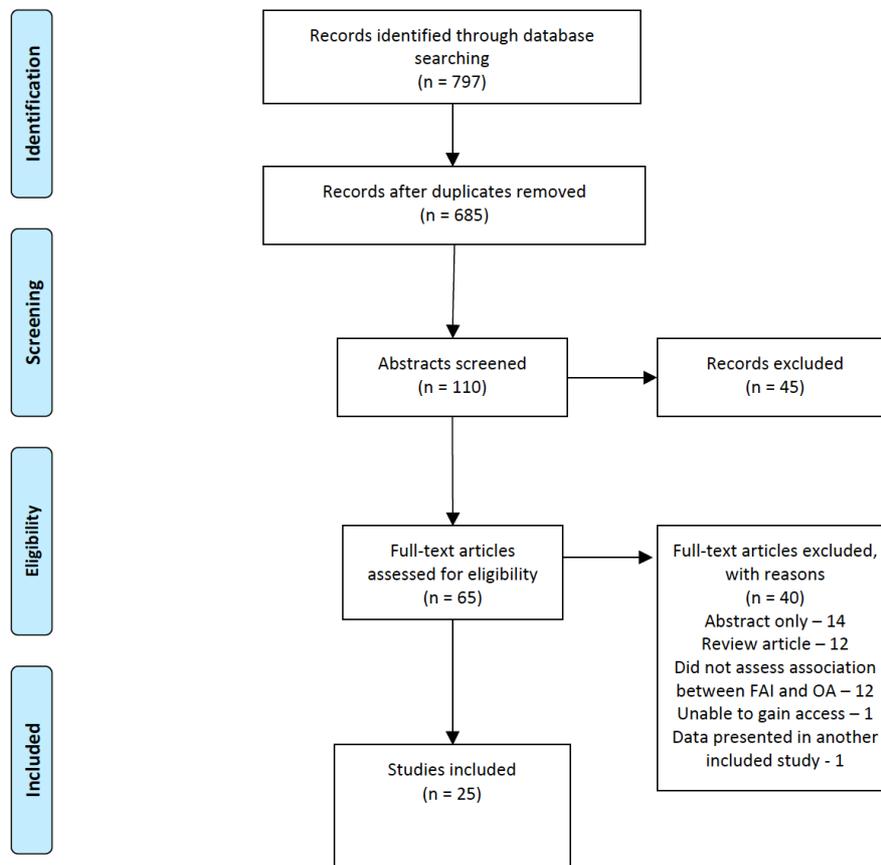
7.3.8 Subgroup Analysis

Analysis of studies assessing subjects with cam or pincer morphology and FAI syndrome were reviewed independently.

7.4 Results

A PRISMA flow diagram of the search is shown in Figure 43. The search returned 685 records after duplicated were removed, following full text review of 65 records, 25 were included.

Figure 43 PRISMA Flow Diagram



7.4.1 Description of Included studies population, by study design

Cohort studies:

Four records reported the results of cohort studies assessing hip morphology and hip OA.

Agricola et al 2012 and 2013 assessed subjects from the Cohort Hip and Cohort knee (CHECK) study in the Netherlands. The CHECK study included subjects aged 45-65 at inception who reported pain or stiffness in their hip or knee but had not yet consulted a GP. At inception of the CHECK cohort, subjects with pathology that could explain their symptoms were excluded (e.g. hip trauma, rheumatoid arthritis, dysplasia, Perthes disease, osteochondritis dessicans, fracture, septic arthritis,

Kellgren and Lawrence (KL) grade 4 or total hip replacement [THR]). Of the original cohort of 1002 subjects, 865 (682 females, 182 males) with imaging at baseline and 5 year follow up were included.^{103,249}

Pollard et al assessed subjects from the Sibkids cohort from the UK. The Sibkids was a cohort of the offspring of subjects where both siblings had received a THR. The Sibkids group were perceived to be at risk of hip OA. The spouses of the Sibkids were also recruited to act as controls within the cohort. Subjects were assessed at baseline and 5 year follow up. 123 Sibkids and 80 spouse hips were available for follow up with a mean age of 52 years and equal numbers of males and females.²⁵⁰

Thomas et al reviewed the Chigford cohort.²⁵¹ The Chigford cohort was set up in 1989 and recruited 1003 females aged 44-67 who were registered at a London GP practice. Participants attended for an AP radiograph at year 2. Their final follow up at 20 years occurred in 2 stages, 1 where subjects were asked whether they had undergone a THR in a questionnaire and another phase where subjects attended for an AP radiograph. Thomas et al report the 20-year follow up data of subjects who had radiographs (n=340 subjects, 634 hips median age 52) and responded to questionnaires (n=734 subjects, 1466 hips, median age 54).²⁵¹

Case control studies

Six records report the results of case control studies assessing subjects with cam or pincer morphology and hip osteoarthritis.

Nicholls et al report an embedded case control study within the Chigford cohort (described above).²⁵² In this study cases were defined as those who had undergone THR (n=31 patients including 40 hips) and controls were 114 randomly selected subjects.²⁵²

Nelson et al conducted a nested case control study within the Johnson County OA Project. This is a regional cohort study, in the USA, set up in 1990 to estimate rates of knee and hip OA in adults over 45 years. The cohort study included 3018 subjects

of whom 33% were African American and 38% were male, the mean age was 62 years. The study followed subjects up at 6 and 13 years with radiographs. This study identified case hips within the cohort by selected subject with hips with KL grade <3 at base line but ≥ 3 or a THR at either follow up. Controls were the hips of age, sex and ethnicity matched subjects or the contralateral hips of case hips with KL grade <3 at all time points. 68 case hips and 168 controls (25% male 28% African American) were included in the study.²⁵³

Goodman et al performed a cadaveric case control study by reviewing a human skeleton collection in the USA. The skeletons were gathered from unclaimed bodies from the Cleveland city morgue between 1893 and 1938. Case hips were identified as those with *post SUFE morphology*; controls were identified as age, gender and race matched skeletons. 306 cases and controls were identified; the mean age at death was 45 years.²⁵⁴

Doherty et al include subjects from the Genetic and Osteoarthritis and Lifestyle (GOAL) study.²⁵⁵ The GOAL study was set up in the UK to investigate gene environment interactions in hip and knee OA. Cases were identified from orthopaedic surgery waiting lists and rheumatology OA clinics, where patients had been referred for 'symptomatic clinically severe OA'. Controls were recruited from lists of patients who had been to hospital for an intra venous urogram and had no hip symptoms or radiographic signs of OA.²⁵⁵ The GOAL study included 965 case hips with a mean age of 68 (50% female) and 1111 controls with a mean age of 64 (46% female).²⁵⁵

Barros et al describe a case control study from a single centre in Brazil. Cases (n= 50 patients, 72 hips, mean age 70, 66% female) were selected from subjects undergoing THR. Cases with OA secondary to inflammatory arthritis, trauma, sepsis, dysplasia, metabolic diseases, Paget's disease, osteonecrosis, or proximal femoral epiphysiolysis and patients with other musculoskeletal diseases affecting the lower limbs were excluded. Controls (n=56 subjects, 112 hips, mean age 71, 88% female) were asymptomatic elderly individuals who were active or retired hospital employees who did not have hip pain or radiographic signs of OA.²⁵⁶

Mamisch et al selected a group of patients with cam (n=6, mean age 33 all male) or pincer (n=7, mean age 36, 4 male) type FAI syndrome undergoing surgery, diagnosed by 2 senior authors. A control group (n=12, mean age 25, 4 male) who did not have evidence of cartilage damage on MRI were also identified. Both groups underwent a delayed gadolinium enhanced MRI of cartilage scan (dGEMRIC - a cartilage imaging technique described in Chapter 8).²⁵⁷

Case series

The search returned 3 records that reported case series. Two studies assessed the contralateral hips of subjects who had undergone a THR and followed up changes over 10 years.^{258,259} Hartokildakidis et al included 96 subjects (31 males) with a mean age at first presentation of 49years.²⁵⁸ Wyles et al included 162 patients (71 male) with a mean age of 47years.²⁵⁹ Bardakos et al assessed subjects referred to a single surgeon with idiopathic OA with a Tonnis grade of 0, 1 or 2 aged under 55years. Subjects were included if they had 2 radiographs more than 10 years apart.²⁶⁰ The mean age, when they entered the study, of the 35 males and 8 females, was 54 years.

Cross sectional:

The search returned 12 records that were cross sectional in design; 4 studies were cross sectional reviews of a cohort study, 6 included patients undergoing surgery and 2 were patients undergoing another form of medical intervention.

Review of cohort study

Gosvig et al included a subset of subjects from the Copenhagen Osteoarthritis Study (COS) in their cross sectional report.²⁶¹ The COS was formed as a sub-study of the Copenhagen City Heart Study III in which participants completed a general musculoskeletal questionnaire.¹⁰⁴ Participants were included in the COS if they had a positive response to $\geq 4/50$ musculoskeletal questions (2939 participants).

Additionally the COS included age and sex matched participants who had positive answers to $\leq 3/50$ musculoskeletal questions (1202 participants).¹⁰⁴ Gosvig et al assessed 3620 subjects (37% male, mean age 61) from the COS having excluded subjects with a THR, Perthes disease, RA or unreadable radiographs.²⁶¹

Nardo et al reviewed the radiographs of subjects recruited in the USA's Cohort study 'Osteoporotic Fractures in Men Study'.²⁶² This included men over 65 from 6 centres.²⁶² Men were invited to undergo clinical examination, which included an AP radiographs, 4215 men out of 5994 in the cohort underwent this examination. Hips were excluded if they had a THR or the radiographs were of insufficient quality. In total 4215 men (8051 hips) with a mean age of 77 were available for analysis. The cohort was designed to be representative of community dwelling ambulatory males over 65 years.²⁶²

Pollard et al 2010 conducted a cross sectional study of subjects within the Sibkids cohort (described above). dGEMRIC scans were performed on a selected group.²⁶³ Of the 123 Sibkids and 80 spouse controls, 25 sibkids and 9 spouses with a mean age of 52 years, underwent dGEMRIC scanning.²⁶³

Reichenbach et al conducted a cross sectional study of male Swiss Army recruits. 1080 subjects underwent questionnaire and clinical assessment, of these 430 were invited to undergo MR examination of which 244 attended (mean age 20 years).²⁶⁴

Patients undergoing surgery

Three studies from Switzerland, Canada and USA included subjects undergoing surgical treatment for FAI syndrome at a single centre.^{32,265,266} Beck et al included 26 subjects with cam morphology (24 males, mean age 32) and 16 subjects with pincer morphology (2 males mean age 40 years), undergoing a surgical hip dislocation.³² Beaulé et al selected 167 patients (129 male) undergoing arthroscopic surgery with a mean age 38 years.²⁶⁵ Johnston et al also selected patients undergoing hip arthroscopy they included 82 patients (47 male, mean age 25).²⁶⁶

Three studies from Turkey, Japan and Canada included subjects undergoing THR.^{93,267,268} Omer et al assessed 1004 patients (314 males) with a mean age of 56 years.²⁶⁷ Takeyama et al assessed 817 patients (158 male) with a mean age of 55 years.⁹³ Tanzer et al assessed 200 patients, the demographic data was not reported.²⁶⁸

Other medical intervention

Kim et al included 117 hips from patients receiving a CT virtual colonoscopy who were under 65 at single centre in the UK.²⁶⁹

Weinberg et al performed an osteology review of 1090 cadaveric hips (940 male) with a mean age at death of 56 years (SD10).²⁷⁰ These hips were randomly selected from a collection of over 3000 humans, housed in Hamann-Todd Osteological Collection (USA), to be representative of adults with hip pain.²⁷⁰

7.4.2 Measures of cam morphology

Twenty-three studies assessed the association between cam morphology and hip OA. Eleven different measures of cam morphology were used; the most frequently used was the α angle, used in 13 studies.

7.4.3 Measures of pincer morphology

The association between pincer morphology and hip OA was assessed in 18 studies. Eleven different measures of pincer morphology were utilised, the most frequently used was the CEA; used in 10 studies.

7.4.4 Measures of FAI syndrome

Three studies assessed subjects undergoing surgery for FAI syndrome.^{32,265,266} In the CHECK cohort Agricola et al highlighted a group of subject synonymous with FAI syndrome, although not formally diagnosed. These subjects had hip pain, internal rotation in flexion less than 20° and an α angle greater than 83°. ¹⁰³

7.4.5 Measures of hip osteoarthritis

The extent of hip OA was determined by one of 9 different measures. The most frequently used measures of OA were the need for THR (n=9) and the KL classification (n=6).

7.4.6 Risk of Bias

Thomas et al and Nelson et al were rated an overall moderate risk of bias.^{251,253} They were both rated as a high risk of bias in category 1; was the studies target population a close representation of the national population. They were also rated a high risk of bias in category 4; was the likelihood of non-response bias minimal. The remaining 23 studies were all rated an overall high risk of bias; see Table 32.

7.4.7 Estimates of Association

The reported association between cam and pincer morphology, and hip OA is reported in Table 33. This table summarises each study, its evidence in support of causality, methodological weaknesses and which categories of the Bradford Hill criteria the study's evidence supports.

The two studies with a moderate risk of bias reported a positive association between an increasing α angle and risk of OA while there was conflicting evidence from the association of pincer morphology and OA.^{251,253}

Thomas et al report a non-linear association between α angle and CEA, and KL grade and need for THR. For every degree increase in α angle over 65° the adjusted odds ratio (OR) of radiographic OA was 1.05 (95%CI 1.01-1.09), and for need for THR were 1.03 (95%CI 1.00-1.07). The odds for a CEA above 35° for either radiographic OA or need for THR were not increased.²⁵¹

Nelson et al report that for every degree increase in the α angle the OR for progression to KL grade ≥ 3 was 1.04 (Males 1.04 [95%CI 1.01-1.07] females 1.04 [95%CI 1.02-1.05]) and for α angle $>60^\circ$ the OR were 3.57 (95%CI 1.17-10.90) in

men and 4.61 (95%CI 2.09-10.16) in women. An increased proximal femoral angle (neck shaft angle) was protective with every degree increase conferring a reduced OR of 0.90 (95%CI 0.81-0.99) in males and 0.97 (95%CI 0.91-1.03) in females. The presence of coxa profunda was protective in males only; OR 0.22 (95%CI 0.07-0.69), while in female the OR was 0.87 (95%CI 0.34-2.20). Acetabular protrusion led to increased odds of KL grade ≥ 3 in females; OR 4.10 (95%CI 1.00-16.8).²⁵³

Table 32 Risk of Bias assessment for included studies

Study	Risk of Bias 1	Risk of Bias 2	Risk of Bias 3	Risk of Bias 4	Risk of Bias 5	Risk of Bias 6	Risk of Bias 7	Risk of Bias 8	Risk of Bias 9	Risk of Bias 10	Risk of Bias 11
Agricola 2012 ¹⁰³	High	Low	High	High	Low	Low	Low	Low	High	Low	High
Agricola 2013 ²⁴⁹	High	Low	High	High	Low	Low	Low	Low	High	Low	High
Bardokos 2009 ²⁶⁰	High	High	High	Low	High						
Barros 2010 ²⁵⁶	High	High	High	High	Low	Low	Low	Low	High	Low	High
Beaule 2012 ²⁶⁵	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Beck 2005 ³²	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Doherty 2008 ²⁵⁵	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Goodman 1997 ²⁵⁴	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Gosvig 2010 ²⁶¹	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Hartofilakidis, 2011 ²⁵⁸	High	High	High	Low	High						
Johnston 2008 ²⁶⁶	High	High	High	Low	Low	High	Low	Low	High	Low	High
Kim 2006 ²⁶⁹	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Mamisch 2011 ²⁵⁷	High	High	High	High	Low	High	High	Low	High	Low	High
Nardo 2015 ²⁶²	High	Low	Low	High	Low	Low	Low	Low	High	Low	High
Nelson 2015 ²⁵³	High	Low	Low	High	Low	Low	Low	Low	Low	Low	Moderate

Oner 2016 ²⁶⁷	High	High	High	Low	Low	High	High	Low	High	Low	High
Pollard 2010 ²⁶³	High	High	High	High	Low	Low	High	Low	High	Low	High
Pollard 2013 ²⁵⁰	High	High	High	High	Low	Low	Low	Low	High	Low	High
Nicholls 2011 ²⁵²	High	High	Low	High	Low	Low	Low	Low	Low	Low	High
Reichenbach 2011 ²⁶⁴	High	High	Low	High	Low	Low	High	Low	High	Low	High
Takeyama 2009 ⁹³	High	High	High	Low	Low	Low	Low	Low	High	Low	High
Tanzer 2004 ²⁶⁸	High	High	High	Low	Low	Low	High	Low	High	Low	High
Thomas 2014 ²⁵¹	High	Low	Low	High	Low	Low	Low	Low	Low	Low	Moderate
Weinberg 2017 ²⁷⁰	High	High	High	High	Low	High	High	Low	High	Low	High
Wyles 2016 ²⁵⁹	High	High	High	Low	Low	High	Low	Low	Low	Low	High

Dark shading indicates high risk of bias.

Light shading indicates moderate risk of bias

No shading indicates low risk of bias.

Items included on the risk of bias tool:

- 1) Was the study's target population a close representation of the national population in relation to relevant variables, e.g., age, sex, occupation?
- 2) Was the sampling frame a true or close representation of the target population?
- 3) Was some form of random selection used to select the sample, OR, was a census undertaken?
- 4) Was the likelihood of non-response bias minimal?
- 5) Were data collected directly from the subjects (as opposed to a proxy)?
- 6) Was an acceptable case definition used in the study?
- 7) Had the study instrument that measured the parameter of interest (e.g., prevalence of LBP) been tested for reliability and validity (if necessary)?
- 8) Was the same mode of data collection used for all subjects?
- 9) Was the length of the shortest prevalence period for the parameter of interest appropriate?
- 10) Were the numerator(s) and denominator(s) for the parameter of interest appropriate?
- 11) Summary item on the overall risk of study bias.

Table 33 Description of included studies and assessment of association with hip OA

Record	Study Design	Summary	Type of assessment made (FAI syndrome, cam, pincer or mixed morphology) other	Definition of cam, pincer or FAI syndrome	Definition of OA	Evidence of association with OA (95% CI)	Weaknesses	Bradford Hill criteria fulfilled
Agricola et al 2012. Cam impingement causes osteoarthritis of the hip: a nationwide prospective cohort study (CHECK) ¹⁰³	Cohort study	Netherlands based CHECK cohort of 865 subjects (682 female, 183 males) aged 45-65year with hip or knee pain or stiffness who were yet to consult their GPs. AP pelvic radiographs measured at baseline and 5 year follow up.	Cam Morphology	AP pelvis AA>60° AA>83°	KL grade 3 or 4 or THR on follow up AP x-ray at 5 years	OR 2.42 (1.15-5.06) OR 9.66 (4.72-19.78)	All patients had hip or knee pain at inception of cohort. High female to male ratio. Degenerative processes could confound low internal rotation in flexion. Not clear which patients had hip pain or knee pain.	Strength Temporality Biological gradient
			Cam type FAI syndrome	AA>83° and internal rotation in flexion <20°		OR 25.21 (7.89-80.58)		
Agricola et al 2013. Pincer deformity does not lead to osteoarthritis of the hip whereas acetabular dysplasia does: acetabular coverage and development of osteoarthritis in a nationwide prospective cohort study (CHECK) ²⁴⁹	Cohort study	See above	Pincer Morphology	AP pelvis CEA >40°	KL grade 3 or 4 or THR on follow up AP pelvis at 5 years	OR 0.28 (0.07-1.21)	All patients had hip or knee pain and inception of cohort. High female to male ratio when more males affected by cam. Not clear which patients had hip pain or knee pain.	Nil
Bardakos et al 2008. Predictors of progression of osteoarthritis in femoroacetabular impingement ²⁶⁰	Case series	Patients seen by a single surgeon in the UK with idiopathic OA under the age of 55 with 2 radiographs more than 10 years apart. 47 hips from 43 patients included (35male 8 female) mean age of 54years at baseline.	Cam morphology	AP radiograph Alpha angle: Medial proximal femoral angle:	Progressions of Tonnis grade	Not significant predictor OR 20.6 (3.4-34.8)	Highly selective sample. Already had some signs of OA at baseline.	Strength Temporality
			Pincer morphology	CEA: Tonnis angle: Cross over sign: Posterior wall sign: Coxa profunda:		Not significant predictor OR 10.2 (1.0-99.8) Not significant predictor Not significant predictor Not significant predictor		

				Acetabular protrusion:		Not significant predictor		
Barros et al 2010. Femoral head-neck junction deformity is related to osteoarthritis of the hip ²⁵⁶	Case control study	Cases: 50 patients (mean age 70years, 17 male) undergoing THR (KL grade 3-4). Their cases contralateral hip, if KL 2 or 3, and 56 retired hospital workers formed the control group (mean age 71 years, 7 male).	Cam morphology	AA Dunn lateral	KL 3-4	Cases; mean AA 66.4° (95%CI 63-70) Controls; mean AA49.1° (47-49)	Large difference in sex distribution of cases and controls. Effect of confounders likely to be greater than effects detected. Bias sampling. Effect of OA cannot be excluded as causes of abnormal morphology.	Nil
			Pincer	CEA		Cases mean CEA 38.8° (37-41) controls mean CEA 39.0° (38-40)		
Beaule et al 2012. Can the alpha angle assessment of cam impingement predict acetabular cartilage delamination? ²⁶⁵	Cross sectional study	Patients treated by a single surgeon in Canada for FAI syndrome. 167 patients (129 male and 38 female hips) mean age 38 years.	Cam type FAI syndrome	AA lateral radiograph	Beck classification >=3 (identified during arthroscopic surgery).	Every degree increase in AA OR 1.04 (1.01-1.08). AA 50-65° OR 1.44 (0.45-4.59). AA >65° OR 4.0 (1.26-12.71).	Only subjects selected for arthroscopic surgery.	Biological gradient
			Pincer type FAI syndrome	CEA		OR 0.94 (0.89-0.99).		
Beck et al 2005. Hip morphology influences the pattern of damage to the acetabular cartilage ³²	Cross sectional study	All hips treated by Ganz between 1996 and 2001 who underwent a surgical dislocation for cam or pincer type FAI syndrome only were included. Excluded cases of tonnis >1, perthes disease, AVN, traumatic or post traumatic disease and previous surgery. 149 hips were included, 26 with isolated pistol grip deformity (24 men, 2 females) mean age 32. 16 isolated coxa profunda (2men 14 women) mean age 40years.	Cam type FAI syndrom	Pistol grip deformity	Damage to labrum, acetabular and femoral cartilage noted during surgery.	Most damage to cartilage at 1 o'clock, mean depth of 11mm, Labrum separated from cartilage in all hips.	Very selective group of patients. No controls.	Plausibility
			Pincer type FAI syndrome	Coxa profunda		Circumferential labral injury. Chondro-labral separation in 5 hips. Depth of chondral injury mean 4mm. Posteroinferior acetabular and femoral head damage noted.		
Doherty et al 2008. Nonspherical Femoral Head Shape (Pistol Grip	Case control study	Cases; radiographic hip OA identified from orthopaedic and rheumatology outpatients (n=965,	Cam Morphology	AP radiograph femoral head neck ratio <1.27	'severe OA' on radiograph or need for THR	Adjusted OR 12.08 (8.05-18.15)	All patients were older.	Strength

Deformity), Neck Shaft Angle, and Risk of Hip Osteoarthritis ²⁵⁵		mean age 68, 50% male) with 'severe hip OA'. Controls; selected from subjects having IV urogram without symptoms or radiographic evidence of hip OA (n=1111, mean age 64, 54% male).		Neck shaft angle 116°		independent of age, sex, BMI, BMD, physical activity and NSA.	Sampling was biased, clinical populations not general population.	
						Adjusted OR 2.31 (1.17-4.56) independent of age, sex, BMI, BMD, and physical activity.		
Goodman 1997 Subclinical Slipped Capital Femoral Epiphysis. Relationship to Osteoarthrosis of the Hip ²⁵⁴	Cadaveric case control study	A skeletal library of 2665 hips from the USA collected between 1893 and 1938 was reviewed. Hips with evidence of post SUFE morphology were identified as cases and age, sex and gender matched controls were identified. 215 case hips identified	Cam morphology	Post SUFE morphology: loss of anterosuperior concavity, increased concavity posteroinferiorly, posterior movement of fovea	OA; presence of osteophytes, erosions, flattening and exposure of trabecular bone graded on a scale of 0-3	Cases: 29% grade 0, 33% grade 1, 25% grade 2, 12% grade 3. Controls: 43% G0, 31% G1, 21%G2, 5% G3. 38% of cases had grade 2 or3 compared to 26% of controls (p<0.005)	No confidence intervals reported. Cadaveric study so no clinical correlation.	Nil
Gosvig et al 2010. Prevalence of malformations of the hip joint and their relationship to sex, groin pain, and risk of osteoarthritis: A population-based survey ²⁶¹	Cross sectional study	Subjects in Copenhagen Osteoarthritis Cohort study. Study included 3620 subjects (37% male, mean age 61).	Cam morphology	Triangular index >= 0mm	Joint space width >2mm	RR 2.2 (1.7-2.8)	Most subjects had symptoms. Lack of coherence- pincer associated with OA and dysplasia not.	Coherence
			Pincer morphology	CEA >45°		RR 2.4 (2.0-2.9)		
Hartofilakidis et al 2010. An examination of the association between different morphotypes of femoroacetabular impingement in asymptomatic subjects and the development of osteoarthritis of the hip ²⁵⁸	Case series	Retrospective review of hips treated by a single surgeon. The contralateral hip was included in this study if they had no hip pain or radiographic signs of OA at baseline. Hips followed up for mean of 18.5 years. Mean age at first presentation was 49years; 31 males and 65 females.	Cam morphology	AP radiograph presence of: Pistol grip deformity Alpha angle >50° women and >68° men NSA< 125°	OA determined by presence of joint space narrowing or marginal osteophytes.	There was no statistically significant difference in the incidence of OA among the groups (p = 0.43, Fisher's exact test)	Convenience sampled-biased No controls.	Nil
			Pincer morphology	Tonnis angle<0° CEA >35° Cross over sign Posterior wall sign				

				Anterior rim prominence				
Johnston et al 2008. Relationship between offset angle alpha and hip chondral injury in femoroacetabular impingement ²⁶⁶	Cross sectional study	Retrospective case series at single site of patients undergoing hip arthroscopy. Comparison of pre operative radiographic findings and intra operative findings. 82 patients (47 men, 35 women), mean age 25 years.	Cam type FAI syndrome	AA cross table lateral	No acetabular chondral defect during surgery	Mean AA 49° (range 38-72)	No controls Retrospective. Single center. Assumed correspondence between findings at arthroscopy and OA.	Nil
					Acetabular chondral defect noted during surgery	Mean AA 55° (range 29-80) p=0.044		
Kim et al 2006. The relationship between acetabular retroversion and osteoarthritis of the hip. ²⁶⁹	Cross sectional study	Single centre cross sectional study of patients under 65 undergoing CT colonoscopy in UK. 52 males, 65 female mean age 52years included.	Pincer morphology	Acetabular anteversion on CT 1/3 way down acetabulum.	Joint space width in superior lateral aspect of acetabulum on coronal reformatted CT.	Mean joint space in patients with retroversion narrower compared to those without retroversion (1.60 mm vs 2.35mm p < 0.0001).	Single time point. Assumption that narrower joint space correlates with OA.	Lack of consistency.
Mamisch et al 2011. Delayed gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC) in Femoacetabular impingement. ²⁵⁷	Case control study	Single centre Swiss study of patients with cam and pincer morphology and selected 'controls'. Subjects underwent dGEMRIC scans. Comparisons made of dGERMIC index.	Cam Morphology	Classification made by 2 senior authors	dGEMRIC index in one of 7 regions.	Reduced dGEMRIC index. Control 643 vs 488ms for cam (p<0.001) Most marked reduction at 1 o'clock region (37% decrease)	Cam fits with model of Beck 05. Pincer does not fit this model. Highly selective of subjects; controls were excluded if signs of degeneration on plain MR.	Plausibility
			Pincer morphology	Classification made by 2 senior authors		Reduced dGEMRIC index. Control 643 vs 462ms for pincer (p<0.001). Global decrease in all ROIs from 21-31%.		
Nardo et al 2015. Femoroacetabular Impingement: Prevalent and Often Asymptomatic in Older Men: The Osteoporotic Fractures in Men Study ²⁶² .	Cross sectional study	Participants identified from osteoporotic fractures in men study; 4215 (8051 hips) males over 65 (mean age 77), 27% reported hip pain.	Cam morphology	AP pelvis x-ray Impingement angle <70° NSA <125°	Croft score (0-IV). Scores >=2 considered OA.	OR 0.99 (0.69-1.4), OR 2.09 (1.2-3.5) Adjusted for age, race, clinic location, body	Males only. Single time point. All subjects over 65-more likely to have developed OA.	Pincer-strength Lack of consistency

						mass index, comorbidity, and health status		
			Pincer morphology	AP pelvis x-ray CEA >39°		OR 1.53 (1.2-1.9) Adjusted for age, race, clinic location, body mass index, comorbidity, and health status		
Nelson et al 2015. Measures of hip morphology are related to development of worsening radiographic hip osteoarthritis over 6 to 13 year follow-up: the Johnston County Osteoarthritis Project. ²⁵³	Nested case control study	Nested case control study from the Johnston County OA Project. This was a cohort study set up in the USA with 3068 subjects representative of the regional population over 45 years. Case hips (n=68hips) selected as those with KL <3 at baseline but >3 at 6 or 12 year follow up. Controls (n=168) were age, sex and ethnicity matched who had KL <3 at baseline and follow up, these included contralateral hips of case hips. Of the included subjects 25% were male and 26% were African Americans.	Cam morphology	AP radiograph AA	KL grade >=3 Adjusted for age, race, BMI and side.	Men OR 1.04 (1.01-1.07) females 1.04 (1.02-1.05). AA >60 Men 3.57 (1.17-10.90) women 4.61 (2.09-10.16)	Subjects were >45 years at cohort conception Controls had upto KL grade 2.	Consistency Biological gradient (AA) Temporality
			Pincer morphology	Proximal femoral angle Coxa profunda Acetabular protrusion Cross over sign	Men OR 0.90 (0.81-0.99) female 0.97 (0.91-1.03) Men OR 0.22 (0.07-0.69) female 0.87 (0.34-2.20) No men with protursio. Female OR 4.10 (1.00-16.8) Men OR 0.56 (0.2-1.7) Female 1.02 (0.5-2.2)			
Nichols et al 2011.		A nested case control study within the Chigford cohort study	Cam morphology	AP radiograph AA	THR at 19year follow up	For every 1° increase in AA RR	Female only	Biological gradient

The Association Between Hip Morphology Parameters and Nineteen-Year Risk of End-Stage Osteoarthritis of the Hip ²⁵²	Case control study	(n=1003). Females aged 44-67 had an AP radiograph at baseline and had telephone follow up at 19years. Cases were defined as subjects who had had THR between baseline and 19year follow up. 114 controls were selected through random number generation.				of THR increased 5.8% (2.3-9.3)	Although embedded in a cohort study with over 1000participants only 40 case hips and 114 controls were identified.	Temporality
			Pincer morphology	CEA		For every 1° decrease in CEA increased risk of THR by 10.5% (2.0-18.2)		
Oner et al 2016. The prevalence of femoroacetabular impingement as an aetiologic factor for end-stage degenerative osteoarthritis of the hip joint: analysis of 1,000 cases ²⁶⁷	Cross sectional study	Retrospective cross sectional study of patients undergoing THR in a single centre in Turkey. Assessed radiographs to determine the underlying cause of end stage OA.	Cam Morphology	Unclear	Need for THR	9.2% of patients had underlying cam morphology	Single centre No clear definitions of morphology.	Nil
			Pincer Morphology	Unclear		3.8% of patients had underlying pincer morphology		
Pollard et al 2010. Localized cartilage assessment with three-dimensional dGEMRIC in asymptomatic hips with normal morphology and cam deformity ²⁶³	Cross sectional study	Participants identified from the Sibkids cohort from the UK. This cohort study included the offspring of parents where both siblings had had a THR. The 'sibkids' group were deemed at risk of OA. The spouses of the 'sibkids' group were also recruited as controls without a congenital risk of OA. This study included sibkids and their spouses with KL grade <2, no pincer or dysplasia and without contraindications to dGEMRIC. 24 sibkids and 8 spouses were included in this study. Mean age 52 Male 18 female 14.	Cam morphology	Cross table lateral radiograph Alpha angle >62.5°	dGEMRIC index in 9-12 o'clock on acetabulum/ dGEMRIC index from 9-3 o'clock	Cam hips 0.95 Normal morphology 1.09 (p=0.0008).	Older population. Highly selective of subjects. To what extent does dGEMRIC index correlate with OA.	Consistency
Pollard et al 2013. The hereditary predisposition to hip osteoarthritis and its association with abnormal joint morphology. ²⁵⁰	Cohort Study	Sibkids (n=123, mean age 52, 50% male) and spouses (n=80 mean age 54, 49% male) cohort (as described above). Included all subjects who attended baseline and 5 year follow up.	Cam Morphology	Cross table lateral AA > 62.5° or an Anterior offset ratio < 0.135.	KL >1	Overall, 12% (48/406 hips) had KL grade 2 OA. A multivariable logistic GEE model adjusted for age, BMI,	Selective population sample. Relatively short follow up. Use of categorical outcomes may lead to loss of sensitivity.	Inconsistent with other studies- no effect of cam but effect of pincer. Temporality
			Pincer Morphology	Centre edge angle > 39.9°, or Acetabular index <4.9°, or an				

				acetabular depth width ratio of >0.57 (males) or >0.65 (females).		gender, sibkid or control status, with additional adjustment for superior femoral osteophyte (cam deformity) or superior acetabular osteophyte (acetabular deformity), gave ORs of 1.13 (0.58-2.22) for a cam deformity and OA, and 2.38 (1.08-5.25) for pincer deformity and OA.		
Reichenbach et al 2011. Association Between Cam-Type Deformities and Magnetic Resonance Imaging-Detected Structural Hip Damage ²⁶⁴	Cross sectional	A cross sectional study of the Sumiswald Cohort of Swiss Army recruits (all male). The cohort was set up at a single recruiting centre for the Swiss Army. Army recruits completed a questionnaire and underwent clinical examination. A random selection of participants were selected with sampling stratified by degree of hip internal rotation in flexion. 57% of subjects invited attended MRI (n=244 mean age 20years)	Cam morphology	MRI radial sequences head neck offset grade 2 or 3	Antero-superior femoral and acetabular cartilage thickness	Cam 3.96mm +/- 0.74 No cam 4.21mm +/- 0.77	Poor measure of OA Males only	Nil
Takeyama et al 2009. Prevalence of femoroacetabular impingement in Asian patients with osteoarthritis of the hip ⁹³	Cross sectional study	Retrospective review of 817 patient, 946 hips, (163 male, 659 female, mean age 55) patients undergoing THR in Japan.	Cam morphology	Alpha angle >60°	Need for THR	Present in 0.4% of subjects.	Do not know prevalence in general population. No controls. Single centre retrospective study	Nil
			Pincer morphology	Acetabular retroversion or coxa profunda		Present in 0.5% of subjects.		
Tanzer et al 2004. Osseous abnormalities and early osteoarthritis: the role of hip impingement ²⁶⁸	Cross sectional study	Single center retrospective review of patients undergoing THR in Canada. 200 patients radiographs, demographics not reported	Cam morphology	Presence of pistol grip deformity on AP radiograph	Need for THR	All patients (125, 65%) where no other cause for OA was identified	No control No temporality Retrospective single center.	Nil

						had pistol grip deformity		
Thomas et al 2014. Subclinical deformities of the hip are significant predictors of radiographic osteoarthritis and joint replacement in women. A 20 year longitudinal cohort study ²⁵¹	Cohort study	The Chigford cohort study was set up in 1989 in London inviting females registered at their GP surgery aged 44-67 to participate. Of 1353 available subjects 734 (1466 hips) had baseline radiographs. 20 year follow up was completed in 2 stages; by questionnaire (734 subjects, 1466 hips) and radiographic assessment (n=340subjects 634 hips).	Cam morphology	AP radiograph alpha angle	1) KL grade>1. 2) Need for THR. Regression model adjusted for age, BMI and baseline joint space.	Radiographic OA and alpha angle, for each degree increase over 65, OR 1.05 (1.01, 1.09) Need for THR and alpha angle for each degree increase over 65, OR: 1.03 (1.00, 1.07)	Females only Cohort inception during late/ middle age. NB repeat of Nicholls et al data but includes full cohort.	Biological gradient Coherence Strength Temporality
			Pincer morphology	AP radiograph CEA		Radiographic OA; for each degree increase in CEA over 34, OR 1.03 (0.92, 1.15) Need for THR: for each degree increase in CEA over 34, OR: 0.97 (0.84, 1.12)		
Weinberg et al 2017. Decreased and increased relative acetabular volume predict the development of osteoarthritis of the hip ²⁷⁰	Cross sectional study	An osteology review of 1090 cadaveric hips (150female, 940 male) with a mean age at death of 56years (SD10). These hips were randomly selected from a collection of over 3000humans to be representative of adults with hip pain. Specimens were excluded if there was evidence of post mortem damage, rheumatological, infectious or traumatic disease. Specimens were graded 0-3 based on degree of edge lipping (osteophyte formation) on both acetabulum and femur.	Cam morphology	AFNO (mm)	Moderate OA score 3-4/6.	Every 1mm increase AFNO (compared to minimal OA) RRR 0.89 (0.82-0.97)	No differences with alpha angle in RRR of OA (statistics not reported). No details on subjects history Not validated method of assessing for OA. Predominantly male.	Nil
					Severe OA 5-6/6	0.91 (0.84-0.99)		
			Pincer morphology	Acetabular over coverage (>1SD of mean of femoral head volume : acetabular volume)	Moderate OA score 3-4/6.	Compared to normal coverage RRR 0.49 0.07 to 3.3		
					Severe OA 5-6/6	Compared to normal coverage RRR 3.3 (1.1-9.7)		

Wyles et al 2016. The John Charnley Award: Redefining the Natural History of Osteoarthritis in Patients With Hip Dysplasia and Impingement ²⁵⁹	Case series	Review of tonnis grade 0 contralateral hips of subjects under 55 years who had undergone a primary THR between 1980 and 1989. Subjects were followed up for 10-35 years.	Cam and or pincer morphology	Unclear	Progression from Tonnis grade 0 to 3 or THR.	Hazard ratio 1.8 (0.7-4.8)	Low numbers Variable follow up No clear definition of cam and pincer Did not distinguish between cam and pincer	Nil
Odds ratio (OR). Hazard ratio (HR). Relative risk ratio (RRR). Centre edge angle (CEA). Anterior femoral neck offset (AFNO). Alpha angle (AA). Kellgren-Lawrence (KL) grade. Total hip replacement (THR)								

7.5 Discussion

In this section of the discussion, I describe the evidence that is sufficient to demonstrate causality of hip OA under each of the Bradford Hill categories, considering cam and pincer morphology, and FAI syndrome separately. An overview of whether sufficient evidence was reached to satisfy the Bradford Hill criteria can be found in Table 34.

7.5.1 Fulfilment of Bradford Hill Criteria

Strength

Bradford-Hill described strength of evidence as his first category.²⁴⁵ In this review, three records show similar strength of evidence to what Bradford Hill quotes (Chimney sweepers 200 times more likely to develop scrotal cancer and smokers 9 times more likely to develop lung cancer).

Agricola et al 2012 reported an OR of progression to KL3 or 4 or THR in subjects with an α angle greater than 83° of 9.66 (4.72-19.78). This study was scored a high risk of bias. The same study reports an OR of 25.21 (7.9-80.6) for progression to KL3 or 4 or a THR in subjects that had features consistent with FAI syndrome. These subjects had hip pain, reduced internal rotation in 90° of flexion and an α angle greater than 83° .¹⁰³

Bardakos et al reported that the odds of progression in Tonnis grade were 20.6 in subjects with a 1° decrease in medial proximal femoral angle, compared to non-cam subjects. However, this small study led to wide 95% confidence intervals (3-35). The study was level IV evidence with a high risk of bias. The sample was highly selective, there were no controls and many subjects already had signs of OA at baseline radiographs.²⁶⁰

The study by Doherty et al also reported a strong effect of cam morphology on the presence of 'severe OA' or the need for the THR; the OR was 12 (8-18).²⁵⁵ This was

designed as cross sectional case control study and therefore it is unable to distinguish between the exposure (lifetime cam) and the outcome (OA). The measure to determine the presence of cam (head neck offset ratio) may have been affected by the morphological changes that occur in the OA process. The study was rated as an overall high risk of bias.

Despite on the surface presenting strong effect, the weaknesses in methodology lead me to the conclusion that only the study by Agricola et al provides evidence demonstrating a large enough effect be supportive of a causal association.

With respect to pincer morphology the greatest reported effect of pincer (posterior wall sign) and OA (progression of Tonnis grade) was Bardakos who reported an OR of 10.2, however the confidence interval was 1.0-99.8.²⁶⁰ Gosvig et al reported the next largest effect of pincer (CEA>45°) and OA (joint space <2mm); they reported a relative risk (RR) of 2.4 (2.0-2.9).²⁶¹ This is far smaller than the magnitude of effect described by Bradford-Hill to satisfy strength of evidence.

Having critiqued these studies and highlighted the lack of other studies reporting strong associations I must make a cautious note that absence of a strong association does not mean there is a lack of causality.

Consistency

In the association between cam morphology and OA there are 14 studies that report an association, while 4 fail to identify an association. Of these 14 studies are the two studies with a moderate risk of bias while the remainder have a high risk.

Of the 14 studies that report a statistically significant association between cam morphology and OA two were from prospective cohort studies, two were (longitudinal) case control studies, five were cross sectional case control studies, two were case series and three were cross sectional studies.^{103,251-257,259-261,263,265,266} There was significant heterogeneity in the study design, definition of cam morphology and definition of OA. The consistency of statistically significant

association between cam and OA does suggest evidence of causality. However, there were four studies, of differing methodology, that failed to find a statistical association.^{250,258,262,270} There is also likely to be a significant publication bias in reporting any association. Despite this, I do believe there is sufficient consistency of the evidence of cam morphology and progression to OA to provide evidence of causality.

With respect to pincer morphology the consistency of the evidence is less clear. Eight studies report that pincer is associated with OA and seven that could not identify an association. The studies that report an association were of differing methodology (one cohort, two case control, one case series and four cross sectional) but all a high risk of bias.^{253,257,259-263,270} The methods they used to define pincer morphology were also different in each study. The seven studies that failed to identify an association between pincer morphology and OA were of differing designs, although they predominantly assessed the CEA (n=6).^{249,251,252,258,260,265,269} Nichols et al and Beaulé et al report a protective effect of an increasing CEA; this isn't surprising seeing as dysplasia (a low CEA) is a recognised cause of hip OA.^{252,265} Given the conflict of evidence with respect to pincer morphology and OA, I am unable to satisfy myself there is consistency of the evidence to be deemed causal.

Specificity

No studies were supportive of disease specificity. In the case of hip OA there are already a number of accepted causes of OA, therefore cam or pincer morphology and FAI syndrome could not demonstrate specificity.^{37,43,50,254,271-273} In order to display specificity the risk factor must be the only cause of the disease.

Temporality

Six studies displayed temporality; two cohort studies, two case control studies and one case series.^{103,251-253,260} Two of the studies had a moderate risk and four a high risk of bias. Four of these studies reported an association with cam morphology and two with the presence of pincer morphology and hip OA. Agricola et al

determined the presence of cam morphology and followed subjects up at five years, Nelson et al followed subjects up for between 6-13 years.^{103,253} It is also worth noting that the studies by Nichols et al and Thomas et al both included data from the Chigford cohort, which had a 20 year follow up.^{251,252}

Two studies of pincer morphology demonstrated temporality. Pollard et al report a multivariate logistic regression from the Sibkids cohort. The OR of KL >1 in the presence of pincer morphology (using a number of different definitions) was 2.38 (95%CI 1.08, 5.25) at 5 year follow up.²⁵⁰ Bardakos et al reported an association with posterior wall sign and OA at 10 year follow up, although the confidence intervals ranged from 1 to 100.²⁶⁰

I believe the evidence from these studies does support the concept of temporality for cam and pincer morphology and hip OA.

Biological gradient

Six studies report a biological gradient with respect to cam morphology and the development of OA.^{103,251-253,265,270} Two of these studies were a moderate risk of bias.

Agricola et al reported that the OR of developing OA in subjects in the CHECK cohort was 2.42 when the α angle was $>60^\circ$ and 9.66 when $>83^\circ$.¹⁰³ In reporting the results of the Chigford cohort Thomas et al state that for every degree increase in the α angle over 65° the OR of developing radiographic OA was 1.05 and 1.03 for needing a THR.²⁵¹ Nelson et al report that for every degree increase in the α angle the OR of developing KL grade ≥ 3 was 1.04.²⁵³ Beaulé et al reported that the OR of having Beck classification ≥ 3 noted during arthroscopic surgery was 1.04 for every degree increase in the α angle. Weinberg et al reported that for every 1mm increase in the anterior femoral neck offset the relative risk of moderate OA was 0.89 and 0.91 for severe OA (i.e. more offset (less cam)- less OA).²⁷⁰

No studies demonstrate a biological gradient with respect to pincer morphology.

Plausibility

Beck et al propose the mechanisms through which cam and pincer morphology, in the setting of FAI syndrome, cause hip osteoarthritis.³² Beck proposed that in cam type FAI syndrome the antero-superior cartilage is injured, while in pincer type FAI syndrome the postero-inferior cartilage is injured. The study by Mamisch et al, using dGEMRIC, supports the mechanism proposed by Beck for cam morphology causing OA.²⁵⁷ However this dGEMRIC study failed to show postero-inferior cartilage degeneration in patients with pincer type FAI syndrome.

Coherence

In this systematic review, no specific study addresses the issue of coherence. The concept of cam and pincer morphology does not conflict with the present understanding of the causes of OA. Abnormalities of the shape of the proximal femur such as SUFE and Perthes disease offer coherence to the theories with respect to cam morphology and the development of hip OA. In the 1960s, 70s and 80s Murray, Stulberg, Solomon and Harris observed that a significant proportion of cases of hip osteoarthritis were *idiopathic*.^{48-50,274} The theories of OA secondary to cam morphology may explain these cases previously considered idiopathic.

Experiment

This systematic review did not return any records that evaluated how altering hip morphology affects the natural history of the disease.

Analogy

This systematic review did not specifically search for records that would provide an analogy. However, the cadaveric study returned in the search by Goodman et al suggests a link exists between SUFE and hip OA.²⁵⁴

An analogy for causality of hip osteoarthritis can be found by looking at the literature for other conditions characterised by alternative hip shapes that are

recognised causes of OA; for example SUFE, Perthes disease and hip dysplasia.⁵⁰ From these examples, it is easy to appreciate that alterations in hip morphology cause OA.

Table 34 Categories of Bradford Hill criteria where evidence is sufficient to demonstrate causality

Bradford Hill criteria	Cam morphology	Pincer morphology	FAI syndrome
Strength	✓	✗	✓
Consistency	✓	✗	✗
Specificity	n/a	n/a	n/a
Temporality	✓	✓	✗
Biological gradient	✓	✗	✗
Plausibility	✓	✓	✓
Coherence	✗	✗	✗
Experiment	✗	✗	✗
Analogy	✗	✗	✗
n/a = not applicable- see text. Dark shading- evidence to satisfy category No shading- insufficient evidence to satisfy category			

7.5.2 Discussion of Results and Methods

In this systematic review I have described the evidence of causality between FAI syndrome, cam and pincer morphology and hip OA. Only two of the included studies were rated as a moderate risk of bias, the remaining 23 were high risk of bias. Despite their methodological weaknesses and sources of bias there was sufficient evidence to suggest that cam morphology causes OA in five of nine Bradford Hill criteria. With respect to pincer morphology and FAI syndrome two of the Bradford Hill criteria and fulfilled.

While the Bradford Hill criteria provide categories for the type of evidence required, they do not stipulate the threshold of evidence that should be judged as significant within each category. The judgments of what evidence is sufficient to satisfy the Bradford Hill criteria in each of the category are my own subjective assessments (see final column Table 33). With regards to pincer morphology the evidence is conflicting. I believe the evidence presently available was insufficient to demonstrate causality. This may be the result of a false negative error and when more evidence of a sufficient quality is available, I would be able to deem the relationship causal. Something that may be contributing to the conflicting evidence

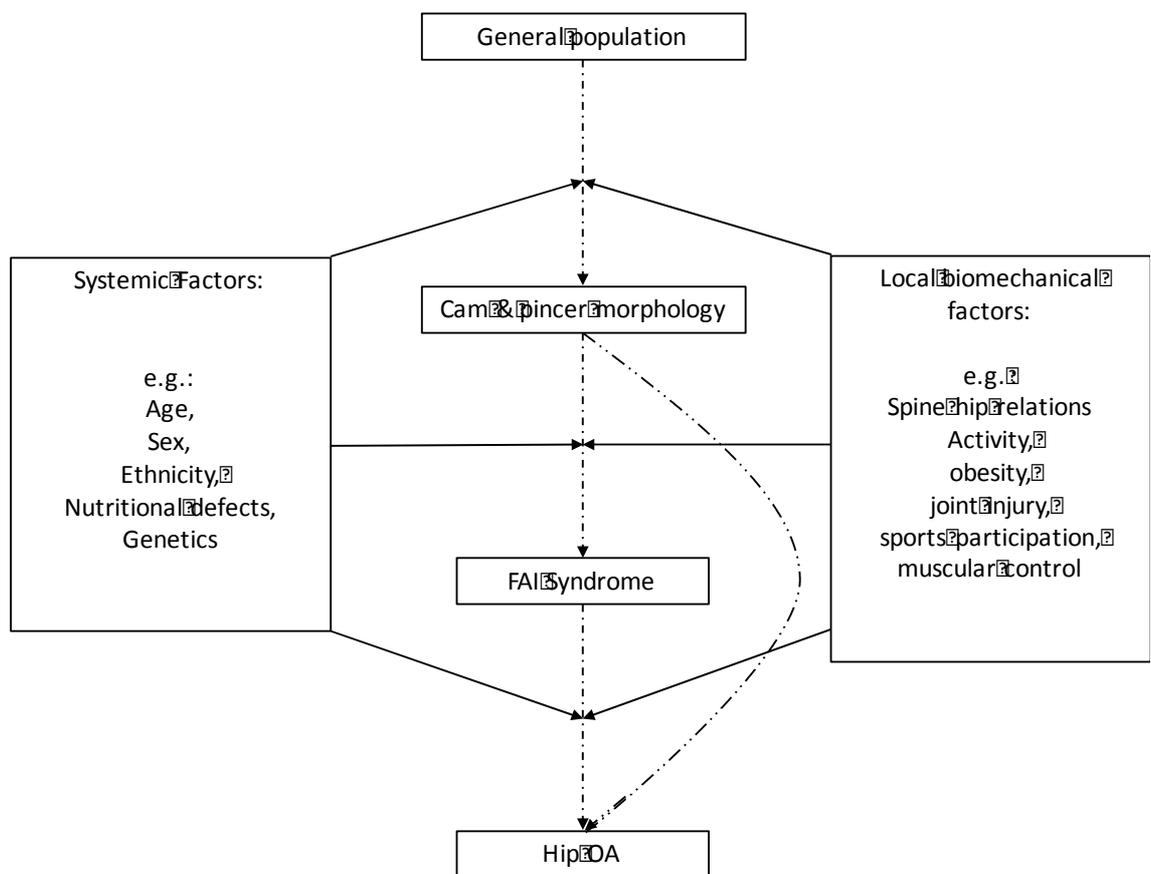
is the contrast in how pincer morphology is defined. In chapters 2, 3 and 4 I have already encountered these issues. With so many different definitions used, of questionable quality, it was not surprising that the evidence of causality was conflicting.

With respect to cam morphology there was more substantial evidence that leads me to believe the association with OA is likely to be causal. In reaching this conclusion I am conscious of some of the weaknesses in the evidence that supports cam morphology. The evidence must be taken in the context of the studies design, risk of bias and how many unique studies are represented across the nine categories. The study reported by Agricola et al 2012 contributed to the evidence in the categories of strength, biological gradient and temporality.¹⁰³ This study was rated a high risk of bias. Other studies that provide evidence for more than one category include Thomas et al, Nichols et al and Nelson et al.²⁵¹⁻²⁵³ In addition to this issue, Thomas et al and Nichols et al both report on data from the same parent cohort study (Chigford).^{251,252} These issues raise the possibility that a few dominant studies are influencing the assessment of causality.

When assessing the literature for a casual relationship between FAI syndrome and OA the supporting evidence was scarce. This is perhaps a reflection of the infancy of FAI syndrome as a disease, preventing the time required for longitudinal studies to be conducted and reported. The lack of evidence of FAI syndrome could also be a reflection of the epidemiology of the disease. If FAI syndrome has a low prevalence, it makes studying the epidemiology of disease more challenging. A traditional approach to understand the relationship would be a case control study. But it may prove difficult to diagnose FAI syndrome retrospectively. It may be simpler to identify proxy measures of FAI syndrome, such as the presence of cam morphology, and draw inferences from there. I believe this may be a step too far given the relationship between cam morphology and FAI syndrome is not understood. In chapter 5 and 6 I report a high prevalence of cam and pincer morphology in different populations. This raises the question of why some subjects with cam or pincer morphology go onto develop FAI syndrome while the majority apparently do not. In chapter 3 the prospect of an unfavorable combination of

morphology and activities was raised. But there may be additional factors that are not understood. There may be a role in the hip musculature, genetics, cartilage or activity that links subjects with cam morphology, FAI syndrome and hip OA. Figure 44 gives an example of the potential factors in this relationship. Understanding this relationship is critical to identify the groups of patients that may benefit from 'hip preservation surgery'.

Figure 44 Possible associations between general population, subjects with cam and pincer morphology, FAI syndrome and OA.



From this systematic review I was unable to identify any studies that fulfilled the criteria of analogy and coherence. In order to identify these types of research additional searches may be necessary to identify other causes of OA that may be attributable to a morphology characteristic, such as SUFE or Perthes disease.^{50,275-}

In chapter 2 I raised concerns about how cam and pincer morphology were being defined in order to report the point prevalence. I anticipated that a similar of issue would be apparent in this study, with different methods being used to define cam and pincer morphology. This was the case. There was an additional factor of different methods and proxy measures being used to define hip OA. OA is defined as a clinical syndrome of joint pain, functional limitations and a reduced quality of life.^{34,35} The studies in this review chose proxy markers of the clinical diagnosis of OA. The most frequently used was the KL classification and the need for THR, however in total there were 9 different measures.

When Bradford Hill described his criteria in 1965 he recognised some flaws. For example with respect to specificity he acknowledged that some multifactorial diseases wouldn't satisfy this requirement. This is the case with hip OA, as described in Chapter 1 there are other causal factors.⁴²⁻⁴⁴ Other criteria with weaknesses include analogy, coherence and plausibility. These criteria are focused on establishing the mechanism by which there is causality. Some authors have sought to amend the Bradford hill criteria to reflect the hierarchy of evidence based medicine and how perspectives have changed over the last 60 years.²⁷⁹ Howick et al described three categories of evidence that build on the Bradford Hill criteria:

- Direct evidence,
- Mechanistic evidence,
- Parallel evidence.

Howick et als description of direct evidence is intended to demonstrate that the size of the effect is not attributable to plausible confounding factors, that there is appropriate temporal proximity between the risk factor and disease, and that there is a dose responsiveness and reversibility to the causal factor.²⁷⁹ The description of mechanistic effects is intended to describe *how* a risk causes disease. This category assesses evidence of a mechanism of action; whether biological, chemical or mechanical.²⁷⁹ The parallel evidence category is a reflection of Bradford Hill's categories to recognise what is already known to support causality. Parallel evidence encompasses the Bradford Hill criteria of coherence, consistency

and analogy.²⁷⁹ These definitions are helpful in interpreting the results of this review. I had previously cautioned about the interpretation of the outcomes of cam morphology given the study design, high risk of bias and the effect of dominant studies being represented across categories. Howick et al's definition of direct evidence sets these concerns in context, particularly when considering if the size of effect is attributable to possible confounding factors. The effect sizes reported are greater than the potential for confounders in the studies I have highlighted. Therefore, there is direct evidence that cam morphology causes hip OA.

This study highlighted the lack of experimental studies to support the hypothesis of causality between cam or pincer morphology or FAI syndrome and OA. Experimental studies such as RCT, provide the most robust method to demonstrate that the size of the effect is not attributable to confounding variables.²⁴⁵⁻²⁴⁸ A RCT that assesses the effect of removing cam or pincer morphology (and treatment for FAI syndrome) and the development of OA would demonstrate whether treatment can alter the risk of OA as well as improve clinical symptoms.

7.6 Conclusion

There is evidence in five of the nine Bradford Hill criteria to demonstrate that cam morphology contributes to causing hip OA. Presently there are no studies that provide experimental evidence to demonstrate that cam morphology or FAI syndrome cause OA. There is insufficient evidence to suggest that the association between pincer morphology and FAI syndrome, and OA is causal.

7.7 Reflections

This systematic review was intended to identify what evidence there is to demonstrate causality of hip OA by cam and pincer morphology and FAI syndrome. I wanted to conduct this review in order to identify the areas where there were gaps in the literature, so that I could plan an appropriate study. This review identified there was presently a lack of experimental studies.

Through the work I conducted in this chapter, I developed skills in critical appraisal of evidence of causality. The Bradford Hill criteria provided an easy structure to assess this evidence. Synthesising the evidence from the included studies required me to appreciate the different aspects of causality, and consider whether each study addressed them. Some studies, despite apparently positive results, were unable to contribute to the evidence of causality in any category (see Table 34). This was due to the robust criteria that I applied.

This review highlighted the range of methods that are used to define OA. Many of these methods are not directly assessing hip OA but markers of the disorder such as radiographic findings associated with OA (e.g. KL grade). This presents a similar issue as to what was identified in chapter 2 with respect to defining cam and pincer morphology. Ideally measuring the presence of hip OA as a clinical disorder should be determined. However, this is labour intensive requiring a history, physical and radiographic examinations. The development of OA is also likely to take many decades following intervention. Associated surrogate measures of OA would be required to conduct such research, in chapter 8 I will consider which proxy markers could be used in a RCT.

In my discussion I acknowledge the weaknesses in my methodology of conducting this review. With hindsight, in order to truly answer the research question and assess each of the Bradford Hill, or the Howick criteria, a search strategy and inclusion criteria for each category is required. While this is a more robust method of answering this question I am unsure whether it would have resulted in a different conclusion. I recognise in the discussion that the search weaknesses may have contributed to deficiencies in the evidence in the analogy and coherence groups, but I did suggest the types of research that might support these arguments. Furthermore these categories are not the critical to demonstrating causality. Far greater weight is given to direct evidence.

Through this chapter, I have developed my research skills of critical appraisal, particularly with respect to epidemiological studies of disease causality. This

systematic review has highlighted the lack of experimental studies, which I hope to address in chapter 8.

8 Is it feasible to undertake an efficacy trial of arthroscopic FAI surgery using cartilage mapping as a proxy outcome?

In this chapter I will determine whether MRI based proxy markers of osteoarthritis alter following treatment for FAI syndrome. This study is a feasibility study designed within an on going randomised controlled trial, comparing arthroscopic surgery to conservative care, for patients with FAI syndrome.

Declarations

I received the following help in writing this chapter:

C Hutchinson, S Wayte and V Sherwood in designing and optimising the MRI sequences used in this study.

V Sherwood conducted an independent unpublished validation study, which I refer to the discussion.

The University of Warwick and University Hospitals of Coventry and Warwickshire NHS Trust sponsored this study.

NHS Research ethics committee approved was obtained 15/WM/0235.

8.1 Introduction

In Chapter 3 the consensus panel stated ‘The long term outlook for patients with FAI syndrome is unknown. However it is likely that cam morphology is associated with hip osteoarthritis’.⁷⁰ This opinion is supported by the systematic review I conducted in Chapter 7. In Chapter 7 I identified evidence to suggest cam morphology causes OA, while the evidence for pincer morphology and FAI syndrome was less clear. While there are studies that suggest cam morphology causes OA there is no evidence to show whether surgical intervention (femoral head neck or acetabular rim reshaping, in the setting of FAI syndrome) alters the natural history. Bradford Hill describes how experimental study provide the best evidence of causality.²⁴⁵ Since Bradford Hill’s description, RCTs have become established as a means to provide the highest level of evidence to assess the effectiveness of healthcare interventions.²⁴⁶⁻²⁴⁸ UK FASHIoN is a RCT that aims to assess the clinical and cost effectiveness of arthroscopic surgery compared to best conservative care.⁸⁰ Its primary aim is to assess changes in patients’ hip related quality of life but not whether surgery alters the natural history of the disease. A RCT that assesses whether surgical intervention for FAI syndrome alters the risk of developing OA would provide the strongest evidence of causality. However conducting such a RCT is not straightforward. It may take decades for patients with FAI syndrome to develop OA. Maintaining follow up rates and keeping patients to their allocated treatments over a long period would be problematic.^{247,280,281} Therefore, we need to consider proxy markers of OA. A proxy or surrogate marker of OA is intended to measure a point earlier in the pathological process. Changes in the detection of a proxy marker can then be extrapolated to suggest difference in the development of OA. In order to understand and select an appropriate proxy outcome I shall revisit the pathophysiology of OA.

OA is defined as a clinical syndrome of joint pain, functional limitations (such as stiffness) and a reduced quality of life.^{34,35} It is characterised by the pathological loss of hyaline cartilage, remodeling of subchondral bone, formation of marginal

osteophytes, synovial inflammation, capsular thickening and weakness of periarticular muscles.^{34,37,42} Prior to macroscopic changes in the hyaline cartilage, alteration in the microscopic architecture occur.²⁸² Cartilage degeneration occurs in three stages in response to mechanical, metabolic or inflammatory insults. The first stage is characterised by the disruption of the macromolecular framework of the extracellular matrix, and an increase in the cartilage water content.²⁸³ Initially there is a decrease in the glycosaminoglycan (GAG) content and alterations in the collagen framework of the cartilage.²⁸³ These changes alter the permeability of the extracellular matrix allowing increased water content. Stage two is characterised by chondrocyte proliferation, anabolic and catabolic activity.²⁸³ Chondrocytes detect the damage in the extracellular matrix and the changed osmolality. They respond by proliferating and synthesising extracellular matrix.²⁸³ Metalloproteases are also stimulated to clear damaged matrix components, however intact matrix may also be broken down.²⁸³ There is the potential during stage two for the processes of cartilage damage and repair to reach equilibrium.²⁸³ This may last for many years or even reverse the process of degeneration. Evidence of a reversal of hip degeneration has been shown in patients who have undergone periacetabular osteotomy of the hip.^{284,285} Failure of the repair process in stage two will lead to progression to stage three degeneration. In stage three there is a progressive decline in the synthetic activity of chondrocytes, chondrocyte death and loss of articular cartilage.²⁸³ At stage three signs of degeneration may be apparent on a plain radiograph and the patient may develop OA.

There are a number of surrogate markers of hip OA progression available to use in clinical research. Advances in MR technology have led to the advent of MRI based surrogate markers of OA; sometimes referred to as physiological MRI. A number of different markers are widely available including T2 mapping, T2* mapping, delayed gadolinium enhanced magnetic resonance imaging of cartilage (dGEMRIC), T1rho and sodium mapping. The National Institute of Health and Care Excellence (NICE) guidelines for OA support the use of MR based outcomes for the purpose of research.³⁵

Sodium mapping is a method of assessing the GAG content of cartilage.²⁸⁶ As GAG is lost the concentration of cations such as sodium also decreases. This loss can only be detected using high field strength MR scanners of at least 3T.²⁸⁷ Sequence times are typically long and the resolution is poor. This can be improved by using 7T scanners, although these are not widely available.²⁸⁷ Sodium mapping has not been used in clinical trials, or to assess the hip joint. The feasibility of using sodium mapping in the knee has been reported.²⁸⁸ Due to the need for 7T MRI scanners, uptake in the use of sodium mapping has been low.

T1rho is a non-contrast method of assessing articular cartilage. It is thought to be sensitive to changes in the GAG content of articular cartilage.^{289,290} The T1rho imaging sequence requires a long duration radiofrequency pulse to be applied to the patient. This is increased to measure the magnetisation decay; which is the T1rho relaxation time.²⁹¹ The technique has been used to detect early OA changes in patients with FAI syndrome.²⁹² Most recently T1rho has been used to report improvements in patients' cartilage quality following surgical treatment of FAI syndrome.²⁹³ The T1rho sequences are not widely available. At our institution we do not have access to the T1rho imaging.

Delayed gadolinium enhanced MR imaging of cartilage (dGEMRIC) is a contrast enhanced imaging technique. The technique requires T1 imaging to be conducted prior to and 30min after the administration of intravenous gadolinium.²⁹⁴ The uptake of the negatively charged gadolinium within cartilage is inversely proportional to the negatively charged GAG content.²⁹⁴ Differences in the pre and post contrast T1 signal are used to assess the cartilage GAG content, assessed by the dGEMRIC index. dGEMRIC is the most widely used of all the physiological MRI techniques to assess changes in cartilage. It has been reported to show changes in the cartilage quality following treatment for hip dysplasia by peri-acetabular osteotomy.^{284,285,295} dGEMRIC is presently been used in two RCT evaluating arthroscopic hip surgery to treat FAI syndrome.^{296,297} Disadvantages of dGEMRIC include that it is time consuming, requires the administration of contrast, inconsistencies due to variability in the uptake of gadolinium (either due to differences in the time interval or cardiac output), and there are concerns that the

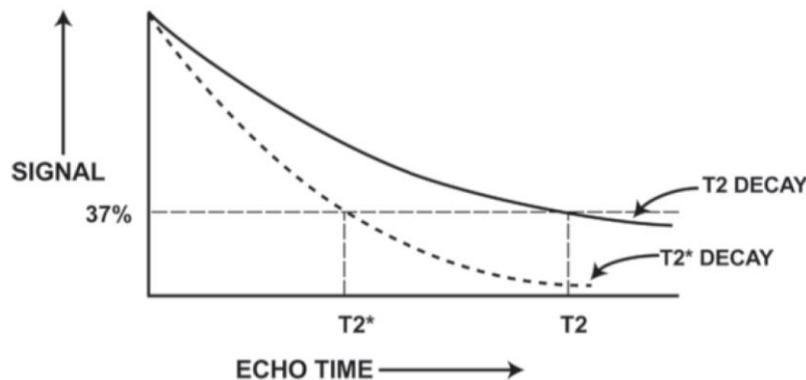
free gadolinium used for dGEMRIC is associated with the development of nephrogenic systemic fibrosis.²⁹⁸⁻³⁰⁰

T2 mapping is a non contrast technique that is sensitive to the water content of the extracellular matrix, this allows indirect assessment of the collagen architecture and proteoglycan content.²⁹⁰ There is a strong relationship between T2 value and the degree of cartilage degeneration.²⁹⁰ In healthy cartilage the extracellular matrix traps water, giving a low T2 signal.²⁹¹ In osteoarthritic cartilage, the matrix breaks up. Therefore there is more free water in the extracellular matrix leading to a greater T2 signal.²⁹¹ While the technique doesn't require the use of contrast it is not thought to be as sensitive to early cartilage degeneration as dGEMRIC and T1rho.²⁹¹ Disadvantages include relatively long acquisition times and the lack of sensitivity in early stages of cartilage degeneration.³⁰¹ T2 mapping is also sensitive to *magic angle* effects. This is the effect the orientation of the collagen fibers to the magnetic field has on the T2 signal.²⁹¹ This renders T2 mapping inaccurate in certain regions of cartilage in the hip.²⁹¹ T2 mapping has been used to evaluate hip cartilage, although not in comparative studies.³⁰²⁻³⁰⁴ The T2 signal was found to differ at different depths of cartilage reflecting the impact of the anisotropy of cartilage.³⁰²

T2* mapping is a gradient echo (GRE) non-contrast imaging technique that measures decay of transverse magnetisation.³⁰⁵ In a GRE MR sequence transverse magnetisation is formed by a single radiofrequency pulse.³⁰⁵ At this point all protons are in phase aligned to the transverse magnetisation.³⁰⁵ The protons then begin to go out of phase; called transverse relaxation.³⁰⁵ The transverse relaxation is primarily caused by adjacent protons spin-spin interactions (intrinsic field), this is the T2 relaxation.³⁰⁵ However there is also an additional dephasing effect caused by local field inhomogeneity- this is called T2* relaxation.³⁰⁵ In a spin echo MR sequence (such as T2 mapping) this is corrected for by the 180° refocusing radiofrequency pulse.³⁰⁵ The 180° refocusing pulse is absent in GRE sequences. Therefore the transverse relaxation measured in a GRE sequence (which are used for T2* mapping) measures the T2 relaxation and relaxation due to local magnetic field inhomogeneity (T2*).³⁰⁵ In T2* imaging the sequences used sample the

transverse relaxation at different time points (echo times). The signal is plotted against the echo time and an exponential decay curve is fitted. T2* is the time at which 37% of the transverse relaxation signal has decayed, see Figure 45. Cartilage assessment by GRE allows an assessment of the cartilage water content (T2 relaxation) and collagen anisotropy (a source of local field inhomogeneity- T2* relaxation), which is disrupted in early OA.³⁰¹ T2* imaging has been shown to correlate with the grade of histological degeneration and intra-operative findings in the hip.^{306,307} The technique is reproducible, sensitive to changes in cartilage quality, has relatively short sequence times, allows 3D imaging and does not require the use of contrast.^{301 308 309} T2* mapping is prone to susceptibility artefacts and magic angle effects.³⁰¹

Figure 45 Plot of Transverse relaxation against time. T2* decay is measured on gradient echo sequence. T2 decay is determined on spin echo sequences. Source Chavhan et al 2009.³⁰⁵



In this study I chose to assess changes in the T2* mapping of articular cartilage as it is non contrast; so minimises the patient risks, has not yet been evaluated in a comparative trial and was available at UHCW.

When assessing complex interventions, such as surgery, RCTs can be challenging to deliver. The Medical Research Council (MRC) published guidelines on the evaluation of complex interventions.³¹⁰ The MRC guidelines report 4 key stages to the evaluation of complex interventions:

1. Development
2. Feasibility/ piloting
3. Evaluation

4. Implementing

As part of stage 1 of developing a complex intervention an understanding of the underlying theory and evidence is required. Through this thesis, I have developed this understanding. In chapters 3 and 4 I have tried to define FAI syndrome and what constitutes cam and pincer morphology. In chapter 7 my systematic review demonstrated there is evidence to suggest that cam morphology is associated with hip OA, while the evidence associating pincer morphology is more conflicting. The underlying theories and mechanisms for this association have previously been proposed by Ganz et al and later by Beck et al.^{4,32} I propose testing these theories to assess whether reshaping surgery alters the progression to joint degeneration.

Prior to assessing whether shape-changing surgery alters the progression to OA in a full RCT, feasibility and pilot RCT are required.³¹⁰ This essential step is often omitted when assessing complex interventions. It is required in order to assess the acceptability, compliance, recruitment and retention rates, protocol viability and effect sizes prior to embarking on a full trial. Therefore I propose a feasibility study, to evaluate whether T2* mapping is a suitable proxy outcome, for assessing whether surgery alters the natural history of cam and pincer morphology associated with FAI syndrome.

8.2 Objectives

- Assess recruitment, and retention rates,
- Assess the integrity of the proposed protocol,
- Assess the feasibility of using the proposed outcomes measures.

8.3 Methods

This study was conducted in accordance with the MRC Good Clinical Practice principles and guidelines, the declaration of Helsinki and Warwick Clinical Trials Unit standard operating procedures.

The study protocol was reviewed by the West Midlands – Edgbaston research ethics committee who gave final approval on 30/7/2015 (15/WM/0235). UHCW research and development approval was obtained on 17/8/2015.

8.3.1 Study Design

I conducted a single centre feasibility assessment, embedded as an observational study within the UK FASHIoN trial.⁸⁰ UK FASHIoN is a multicentre, pragmatic, superiority, 12 month, 2 parallel arm, RCT assessing the clinical effectiveness of arthroscopic surgery versus best conservative care (physiotherapy) for FAI syndrome. Participants recruited to UK FASHIoN at UHCW were invited to participate in this observational study. As part of this study participants had an MRI scan which included T2* mapping, before and after treatment, in order to assess changes in their cartilage.

8.3.2 Eligibility Criteria

UK FASHIoN participants recruited at UHCW who were able to undergo a MRI scan were invited to participate in this study. The eligibility criteria for UK FASHIoN are:

Inclusion Criteria

- Age ≥ 16 (no upper age limit);
- Symptoms of hip pain - patients may also have symptoms of clicking, catching or giving way;
- Radiographic evidence of pincer- or cam-type FAI on plain radiographs confirmed with cross sectional imaging, defined as:
 - Cam morphology: an alpha angle $>55^\circ$ ⁶²
 - Pincer morphology: a lateral centre edge angle $>40^\circ$,³¹¹ or a cross over sign on the AP radiograph of the pelvis ⁶¹
- The treating surgeon believes the patient would benefit from arthroscopic FAI surgery;
- The patient is able to give written informed consent and to participate fully in the interventions and follow-up procedures.

Exclusion Criteria

- Evidence of pre-existing osteoarthritis, defined as Tonnis grade >1, ³⁹ or more than 2mm loss of superior joint space width on antero-posterior pelvic radiograph;⁶⁹
- Previous significant hip pathology such as Perthes' disease, slipped upper femoral epiphysis, or avascular necrosis;
- Previous hip injury such as acetabular fracture, hip dislocation or femoral neck fracture;
- Previous shape changing surgery (open or arthroscopic) in the hip being considered for treatment.

8.3.3 Recruitment

I invited patients who were randomised in UK FASHIoN to a study information consultation when they attended hospital for treatment (either physiotherapy or surgery). They were provided with a participant information sheet and signed the study consent form.

Recruitment to the UK FASHIoN pilot trial commenced in 2012, with recruitment to the main study commencing in September 2014. Recruitment to this observational study commenced in August 2015 and ceased in June 2016.

8.3.4 Treatment

Arthroscopic Surgery

Arthroscopic hip surgery was performed under general anaesthesia in a lateral position. Cam or pincer morphology and consequent soft tissue pathology were treated as deemed necessary by the treating consultant surgeon.

Patients were discharged from hospital when they could walk safely, typically with crutches (usually within 24h hours). On discharge all patients were referred for outpatient physiotherapy.⁸⁰

As part of the UK FASHIoN trial I convened an independent panel of experts who assessed the success of shape changing surgery. The panel consisted of: Marc Philippon (USA), John O'Donnell (Australia), Martin Beck (Switzerland) and Charles Hutchinson (UK). The panel were presented with information from each subjects' operation note, intra operative photos and post operative MRI scans. Surgery was rated as satisfactory, borderline or unsatisfactory.⁸⁰

Personalised Hip Therapy

A package of *best conservative care* was developed during the FASHIoN feasibility study as the comparator arm to arthroscopic surgery.^{7,74} This consists of a physiotherapist led programme delivered over a minimum of six sessions over 12 weeks and up to 10 sessions over 6 months. The package; named Personalised Hip Therapy (PHT) consists of 4 core components:

- A detailed patient assessment
- Education and advice and FAI syndrome
- Help with pain relief, including the option of an intra articular steroid injection
- An exercise based programme that is individualised, supervised and progressive.

Timing of Treatment

Treatments were to start as soon as possible after randomisation. In the FASHIoN pilot study the participants allocated surgery underwent treatment in a mean of 10 weeks while participants undergoing PHT commenced treatment in 4 weeks.⁷

8.3.5 Outcomes Measures

Feasibility assessment

Recruitment and retention

The number of participants recruited, as a proportion of those eligible was determined. Numbers of eligible patients was established by screening new patient

clinic lists. The retention of participants to the 12-month outcomes was determined, as a proportion of recruited subjects.

Protocol Delivery

The viability of the study protocol was measured by assessing:

- Time delays to intervention and follow up imaging,
- Cross over rates,
- Success of shape changing surgery; determined by the UK FASHIoN surgical review panel.⁸⁰

Feasibility of T2* mapping

The feasibility of using T2* mapping was determined by:

- Quality of data from T2* maps ROI; determined by the range of T2* values of voxels within the T2* map. This is a measure of:
 - Imaging quality (signal:noise) of each of the 16 echo times
 - Fitting of the T2* decay curves
 - The generation T2* maps
 - Identifying and selection of appropriate of regions of interest
- The mean, standard deviation and effect size between intervention arms of T2*.

Efficacy Assessment

Primary Outcome

The primary outcome measure was differences in the T2* map values in the antero-superior aspect of the hip joint between baseline and 1 year following treatment.

T2* mapping was chosen as a valid and reliable surrogate marker of cartilage health. It has been shown to correlate with macroscopic and microscopic signs of

cartilage degeneration.^{306,307} T2* maps were made in the antero-superior weight-bearing portion of the hip joint,³¹² this area was chosen as it correlates with the area of the joint most frequently associated with cartilage degeneration in FAI.^{4,32}

Secondary Outcome Measures

- Differences in T2* map values of cartilage in the antero-inferior, postero-superior and postero-inferior aspect of the hip joint 1 year following treatment.
- Differences in Hip Osteoarthritis MRI Scoring system (HOAMS) scores 1 year following treatment.³¹³
- Differences in cartilage thickness 1 year following treatment assessed by techniques described by Reichenbach.²⁶⁴

The NICE guidelines for OA state that when selecting outcomes for research it may be appropriate to use MRI features of OA or changes in joint space narrowing.³⁵ Therefore in addition to measuring T2* value I measured the hip osteoarthritis MRI scoring system (HOAMS) and cartilage thickness.

HOAMS assesses cartilage morphology, bone marrow oedema, subchondral cysts, osteophyte formation and labral degeneration as semi quantitative methods of scoring all hip joint features of OA. It has been shown to be a reliable and valid measure of hip OA that correlates to symptoms.³¹³ The HOAMS system rates each of these features at different areas of the hip joint with scores of 0 representing normal and between 1 and 4 increasing pathology, depending on which feature is assessed. Total possible scores range from 0-16 (not continuous data).³¹³

Cartilage thickness is a recognised surrogate marker of joint health, with reducing thickness associated with progression to OA.³¹⁴ Cartilage thickness assessed on plain radiographs is associated with clinical outcomes following treatment for FAI syndrome.⁶⁹ Changes in thickness has been used in other studies assessing different joints, including the knee, as a surrogate marker of OA progression.³¹⁵⁻³¹⁷ Reichenbach assessed the combined femoral and acetabular cartilage thickness in

a population of Swiss army recruits and found it was reduced in patients with cam morphology.²⁶⁴ Reichenbach et al showed that the combined anterosuperior cartilage thickness was 0.19mm thinner in subjects with cam-type morphology compared to those without.²⁶⁴

Imaging Protocols and Processing:

CH (Consultant Radiologist), SW (Senior MRI Physicist) and VS (Junior MRI Physicist) designed the MRI imaging protocols. Imaging was conducted on a 3T GE Healthcare (Chicago, USA) MRI scanner with a 16 channel body wrap coil.

The following MR sequences of the hip being treated were used:

- Axial oblique T1 fat saturated; Field of view (FOV) 18x18cm, echo time (TE) 10.2ms, relaxation time (TR) 840ms, slice thickness 2mm, flip angle 111, matrix 320x224.
- Coronal oblique proton density fast spin echo; FOV 18x18cm, TE 17.9ms, TR 2000ms, slice thickness 2mm, flip angle 111, matrix 320x224.
- Sagittal proton density fast spin echo; FOV 18x18cm, TE 17.9ms, TR 2000ms, slice thickness 2mm, flip angle 111, matrix 320x224.
- Sagittal spoiled gradient echo three-dimension T1 fat suppressed; FOV 18x18cm, TE 3.8ms, TR 7.9ms, slice thickness 1.2mm, flip angle 10, matrix 320x224.
- Sagittal three dimensional T2* (GRE), 16 different TE were used from 2-38ms, FOV 18x18cm, TR 39.5ms, slice thickness 2.4mm, flip angle 15, matrix 128x224.

The DICOM files were exported to a GE Healthcare ADW workstation. GE Healthcare Functool software was used to generate the T2* maps on the ADW workstation. This process involves combining the 16 different TE sequences into one sequence. In the combined sequence the data for each voxel is represented on a graph of signal (transverse relaxation) against TE. The Functool software fits an exponential signal decay curve (of best fit) to the values on the graph; see Figure 52. The T2* value for each voxel is a measure of the time taken for 37% loss of the

transverse relaxation. The raw data decay curve will never reach zero due to background MR signal (noise), which needs to be subtracted to generate the signal decay curve. Functool automatically subtracts the noise when fitting the decay curve. T2* maps generated in Functool were exported as DICOM files. OsiriX viewer (Geneva, Switzerland) version 8.0.1 was used to draw regions of interest (ROI) on the T2* maps.¹⁹¹ This was completed using previously described techniques in a staged process:³⁰⁶

1. T1 fat saturated SPGR 3D sequence was used to identify the transverse acetabular ligament (TAL) in the sagittal plane.
2. The mid point of the femoral head was identified on multi-planar reconstructions of the T1 fat saturated SPGR 3D sequence.
3. In order to provide a consistency in the size and location of the ROI a point from the centre of the femoral head perpendicular to the TAL in the sagittal plane divided the acetabulum into an anterior and posterior half.
4. The angle from point perpendicular to the TAL to the anterior and posterior labro-condral junctions was measured and divided into 4. This angle was used to divide each half of the acetabulum into four zones. Each formed a ROI which consisted of the combined femoral and acetabular cartilage; see Figure 50.
5. These ROI were saved and imported onto the T2* maps. Mean and standard deviation for T2* value of each ROI were recorded. Colour T2* maps were generated for illustrative purposes.
6. T2* values in the eight ROI were measured on three consecutive sagittal slices centred on the mid point of the femoral head.

HOAMS was measured according to the protocol described by Roemer et al.³¹³

Cartilage thickness was measured on the sagittal slice corresponding to the mid point of the femoral head. Measurements were made at the mid point of the acetabulum and the anterior and posterior labro-chondral junctions.²⁶⁴

8.3.6 Statistical analysis

Sample Size

There are currently no published studies assessing change in T2* value in patients undergoing treatment for FAI syndrome. This study aimed to assess the feasibility of the technique and the data variability including any treatment effects, prior to a full trial. As such no formal power calculation was performed. I aimed to recruit for 10 months, recruiting 20 patients. This is based on a recruitment rate of 2.1 patients per month, which was achieved in the FASHIoN pilot study. This should enable an assessment of the variability of the data and some reasonable precision in estimation of treatment effects.

Statistical Analysis Plan

The main analysis investigated differences in the primary outcome measure between the two interventions on an intention-to-treat basis (ITT), 12 months following treatment. As this is a pilot study, the main analysis was exploratory in nature. The aim being to assess the size and direction of observed differences between the two interventions, and the variability and distribution of the outcome measures. Baseline data; including age, sex and impingement type, was summarised to check comparability between treatment arms. This is a relatively small study, so group means were unlikely to be estimated with great precision. A paired t-test was used to assess the change in the T2* scores between baseline and 1 year, in each of the treatment arms. Tests were two tailed with an alpha value of 0.05. Given the small sample size it was not be possible to perform a multiple regression analysis. However, in a full trial a multiple linear regression analysis would be used to assess differences in the change in T2* scores, between the two treatment arms. Regression models would adjust for baseline T2* scores, gender and FAI type. In addition to the assessment of the primary outcome measure, analogous reporting was performed for the secondary outcome measures (cartilage thickness and HOAMS score). The statistical analysis will be carried out using SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Mac, Version 22.0. Armonk, NY: IBM Corp).

8.4 Results

Research ethics and final UHCW research and developmental approval for this study was obtained on the 17th of August 2015. In September 2015, work began on upgrading the only 3T MRI scanner at UHCW, on which the imaging was performed, to a new 3T scanner. This work took 4 months to complete. Following this period there was a priority for clinical imaging (in order to catch up on the back log) therefore research scanning was not feasible for several more weeks. Once access to research scanning was feasible the protocols for T2* mapping needed updating on the new scanner. In February 2016 UK FASHIoN was due to complete recruitment. Due to the issues with access to the 3T scanner I decided to amend my original study design and only perform follow up MRI scans on study subjects 12 months following intervention, at which stage the 3T MRI scanner would be available once more. Therefore no study subject had a baseline MRI scan with a T2* mapping sequences.

8.4.1 Recruitment and Retention

The UK FASHIoN trial recruited 351 participants over a 4-year period from 24 sites. UHCW recruited 81 of these participants. During the period I was recruiting into this study, UK FASHIoN recruited 30 patients at UHCW. Of these, 1 patient was not eligible due to the presence of a cochlear implant. Figure 46 displays a CONSORT diagram for this study. Table 35 reports the success rate of recruitment for eligible subjects in UK FASHIoN and the retention to the 12-month follow up for this study.

Figure 46 CONSORT Diagram

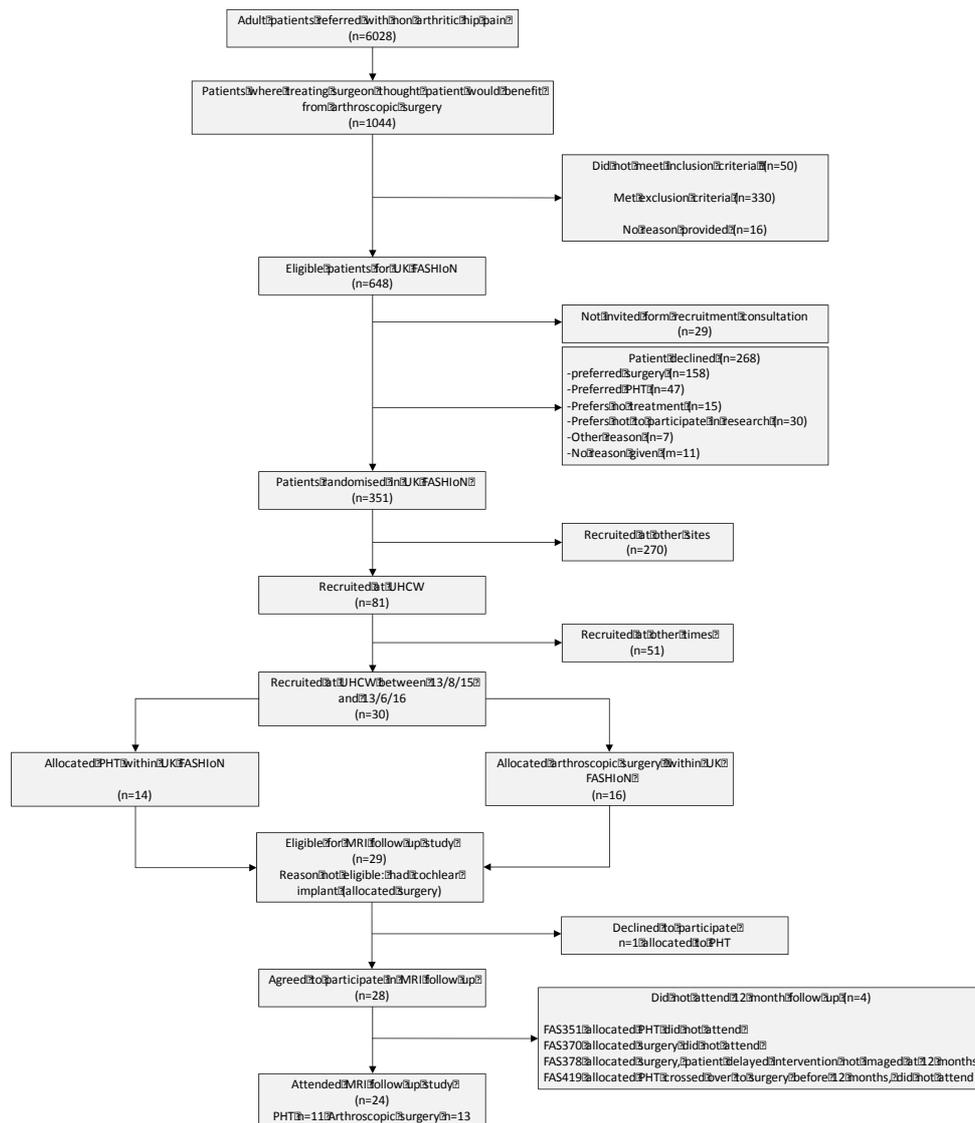


Table 35 Recruitment Success in UK FASHIoN and MRI Follow up

Site	Eligible patients	Patients approached	Recruited to UK FASHIoN	Eligible for UK FASHIoN during recruitment	Randomised in UK FASHIoN during recruitment	Attended 12 month MRI follow up	% eligible who attended 12 month MRI follow up	% Eligible for UK FASHIoN who were retain for 12 month MRI
1	118	115	81	41	30	24	83%	59%
2-24	530	504	270	n/a	n/a	n/a	n/a	n/a

8.4.2 Baseline Characteristics

The baseline demographics between the treatment groups in this study and the UK FASHIoN study are summarised in Table 36. Despite randomisation subjects in the

surgical group in this study had a reduced mean iHOT-33 compared to those allocated PHT. There were no other major differences in the baseline demographics between the PHT and surgery groups or between this study and the main UK FASHIoN trial. Baseline T2* values were not available in view of the issues with the change of the 3T MRI scanner at UHCW, however measurements of cartilage thickness and HOAMS scores were made on the baseline MRI scans that were available. These scans were not optimised for research.

Table 36 Baseline demographics

		UK FASHIoN			MRI follow up study		
		Surgery	PHT	Total	Surgery	PHT	Total
		(n=171)	(n=177)	(n=351)	(n=13)	(n=11)	(n=24)
Age	Mean	35.4	35.2	35.3	37.1	38.4	37.7
	SD	9.7	9.4	9.6	12.8	10.9	11.7
Gender	Male	100 (58%)	113 (64%)	215 (61%)	9 (69%)	8 (73%)	17 (71%)
	Female	71 (42%)	64 (36%)	136 (39%)	4 (31%)	3 (27%)	7 (29%)
Impingement Type	Cam	129 (75%)	133 (75%)	262 (75%)	11 (85%)	8 (73%)	19 (79%)
	Mixed	29 (17%)	30 (17%)	59 (17%)	2 (15%)	2 (18%)	4 (17%)
	Pincer	13 (8%)	14 (8%)	27 (8%)	0 (0%)	1 (9%)	1 (4%)
iHOT33	Mean	39	36	37	32	44	38
	SD	20.9	18.2	20.0	19.8	24.9	22.6
HOAMS	Median	n/a	n/a	n/a	6	8	6
	IQR	n/a	n/a	n/a	3- 9	6- 10	3- 10
Mean cartilage thickness	Mean	n/a	n/a	n/a	2.5	2.6	2.6
	SD	n/a	n/a	n/a	0.3	0.6	0.5

8.4.3 Study Delivery

The median time between the baseline MRI and randomisation was 205 days (IQR32-285); see Table 37 and Figure 47. The time between randomisation and treatment was longer in the surgery group (median 185 days) compared to the PHT group (median 25 days); see Table 37 and Figure 48. The time between treatment and 12-month follow up was comparable between groups; see Table 37. One subject crossed over between intervention arm before the 12-month follow up; they subsequently did not attend MRI follow up.

Table 37 Time between Baseline MRI, randomisation, treatment and follow up MRI

	PHT	Surgery	Total
Median days between baseline MRI and randomisation (IQR)	189 (65-274)	220 (32-281)	205 (32-285)
Median days between randomisation and intervention (IQR)	25 (22-45)	185 (154-186)	76 (29- 185)
Median days between intervention and follow up (IQR)	366 (352-379)	371 (360-376)	370 (352-276)

Figure 47 Time between baseline MRI and randomisation

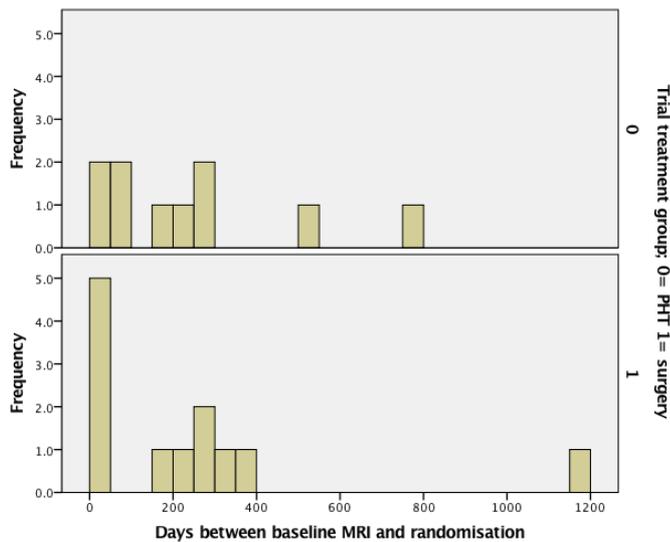
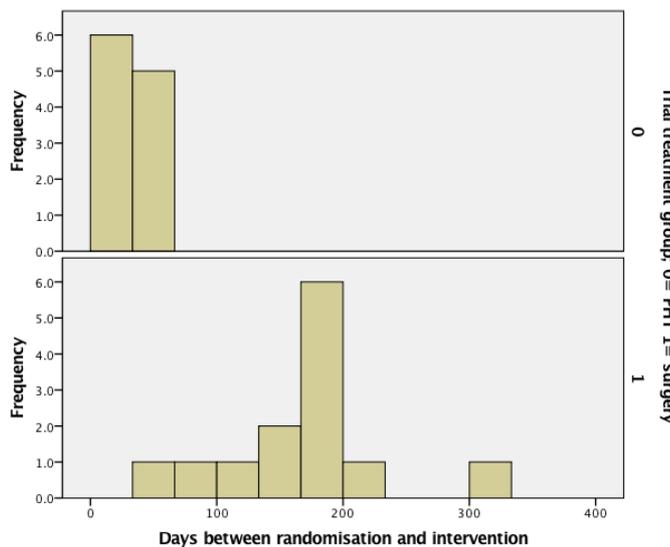


Figure 48 Time between randomisation and treatment



8.4.4 Success of shape changing surgery

The judgment of the surgical review panel, comparing subjects included in this study with the all patients treated with surgery in FASHIoN, is summarised in Table 38. Surgery was judged to be satisfactory in 85% of cases in this study.

Table 38 Outcome of Surgical Review Panel

	Number of cases (percentage of all cases reviewed)		
	Satisfactory	Borderline satisfactory	Unsatisfactory
Included subjects (n=13)	11 (85%)	2 (15%)	0
All FASHIoN subjects (n=121)	85 (70%)	20 (17%)	16 (13%)

8.4.5 Feasibility of outcome measures of efficacy

Follow up MRI scans were performed in line with the agreed protocol. The T2* maps were generated (see Figure 49) using the GE workstation Functool software. When ROI were drawn (see Figure 51), in some individuals erroneous and impossible results were noted (e.g. -250ms; see Figure 39). Where this occurred, the voxels with the erroneous results were identified, and the ROI was redrawn excluding them. The voxels responsible for these erroneous results typically did not have a smooth decay curve; see Figure 52 and Figure 53. These voxels with poorly fitting decay curves, and consequently erroneous results, were typically identified at the junction between the subchondral bone and the articular cartilage.

The T2*, HOAMS scores and cartilage thickness of the follow up MRIs is reported in Table 39 and Table 40. In the antero-superior portion of the acetabulum (ROI 1) the mean T2* value at 12 months in the surgery group was 12.2 (SD3.3) and 12.7 (SD3.2) in PHT. In all regions (ROI 1-8) the between group difference at 12 months was negative, indicating the PHT group had higher T2* values compared to surgery. Higher T2* values are associated with less cartilage degeneration. The HOAMS scores in the PHT group reduced (improved) from a median of 8 to 6, while in the surgery group they increased from 6-7. There was a reduction in the mean cartilage thickness in both groups. There were no statistically significant between group differences.

Figure 49 T2* Map generated in Funtool. In this illustration the T2* values for each voxel are represented by different colours; see key on left side of image. The dark red colour represents a T2* value of 30ms and the dark blue represent a T2* value of 0ms.

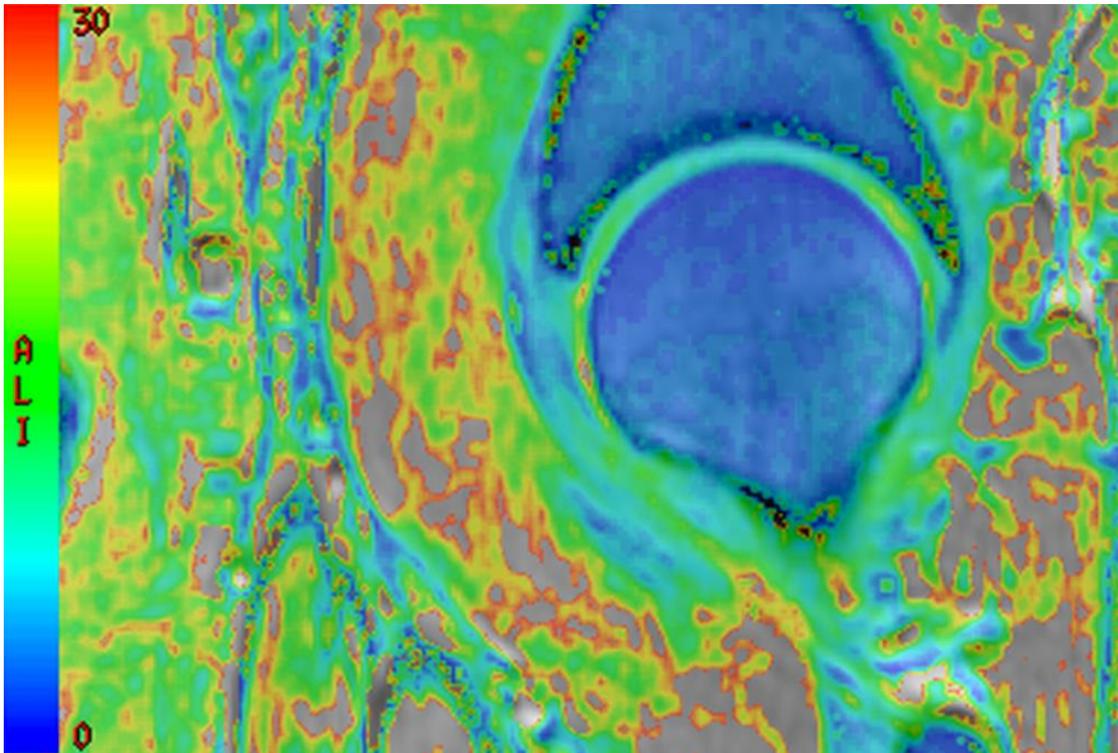


Figure 50 Regions of interest drawn using T1 fat saturated SPGR 3D sagittal slice in line with mid point of femoral head. The 90° angle is in line with the transverse acetabular ligament. ROIs were labeled clockwise; ROI 1 in the anterior most aspect to ROI 8 in the most posterior aspect.

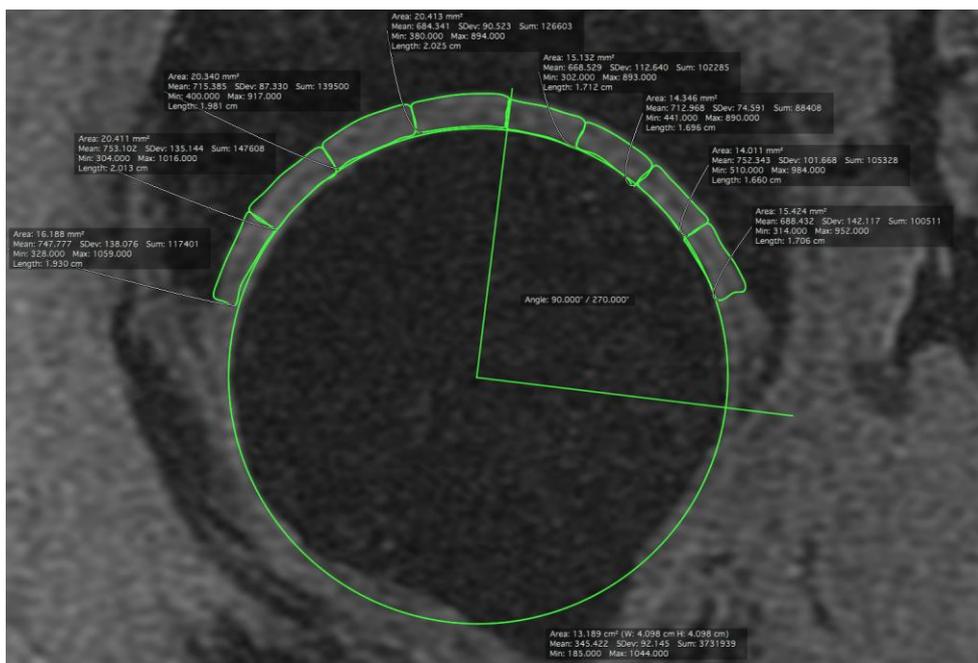


Figure 51 T2* Map generated in Functool. In this illustration the T2* values for each voxel are represented by different colours; see key on left side of image (different key to Figure 37). The dark red colour represents a T2* value of 64ms and the dark blue represent a T2* value of 0ms. Note poor map fit at junction between acetabular subchondral bone and articular cartilage where the voxel T2* value is outside the scale and therefore displayed in black

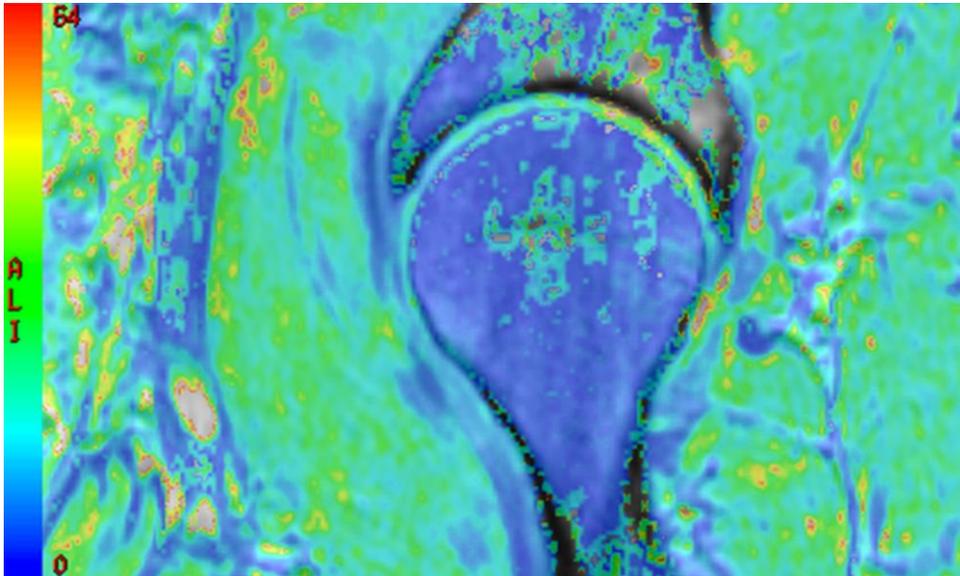


Figure 52 Plot of transverse relaxation signal (y axis) against TEs (x axis) for a single ROI. The green line displays the raw single. The red line displays the exponential decay curve fitted by Functool. This graph displays a well fitting signal decay curve.

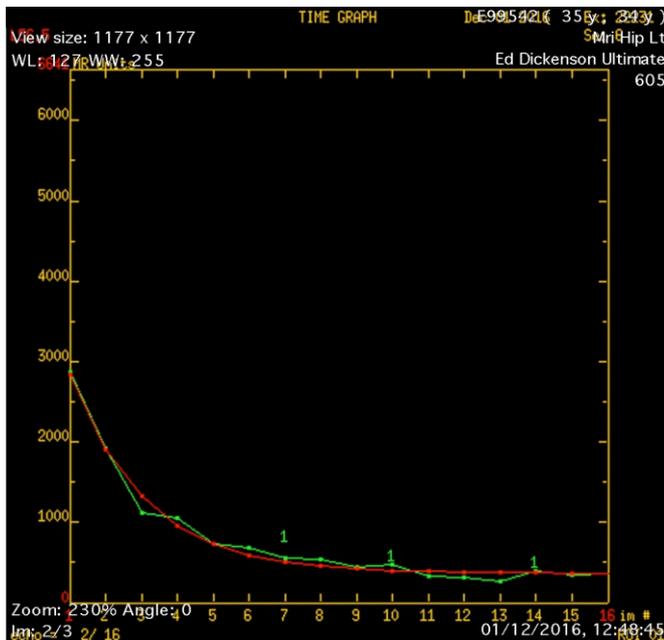


Figure 53 Plot of transverse relaxation signal (y axis) against TEs (x axis) for a single ROI. The green line displays the raw single. The red line displays the exponential decay curve fitted by Functool. This graph displays a poorly fitting signal decay curve; this is likely to have provided the impossible values for T2*.

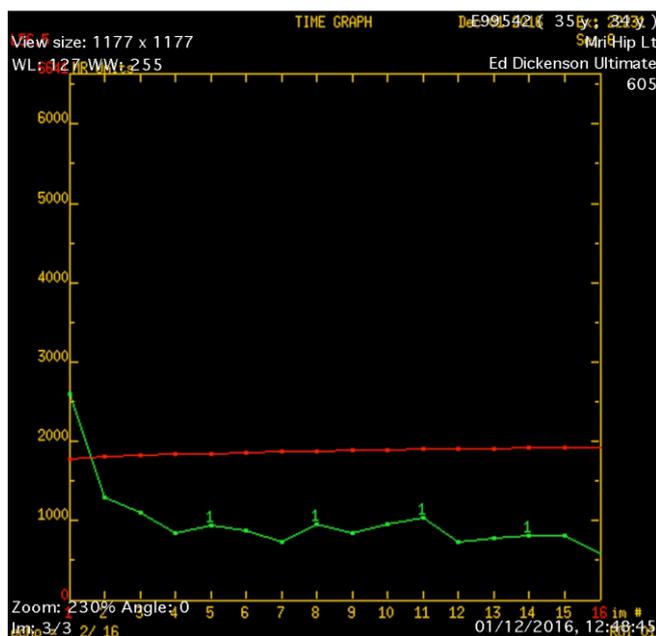


Table 39 Follow up MRI T2* measurements

		PHT		Surgery		Difference	
		Mean	SD	Mean	SD	Raw	p value
Raw T2*	ROI 1	12.7	3.2	12.2	3.3	-0.50	0.520
	ROI 2	11.8	3.7	10.5	2.7	-1.30	0.097
	ROI 3	12.2	5.8	8.7	3.0	-3.50	0.002
	ROI 4	11.3	5.1	9.5	4.6	-1.80	0.122
	ROI 5	13.4	8.3	9.6	3.0	-3.80	0.010
	ROI 6	14.2	6.3	11.1	4.3	-3.10	0.016
	ROI 7	15.6	5.9	13.2	4.8	-2.40	0.058
	ROI 8	14.4	5.7	14.1	4.1	-0.30	0.780
Adjusted T2*	ROI 1	-0.4	7.0	-2.7	4.8	-2.3	0.104
	ROI 2	0.8	0.3	0.9	0.3	0.1	0.175

Adjusted T2*; the T2* value for the ROI (1 or 2 respectively) representing the antero-superior cartilage was subtracted from the mean T2* value in the central aspect of the hip (ROIs 4 and 5). The more positive the value the worse the anterosuperior cartilage quality compared to the central cartilage quality.

Table 40 Changes in HOAMS and Cartilage thickness between surgery and PHT

	Treatment arm	Pre-treatment	Post-treatment	Change (95% CI)	Significance	Between groups difference (95% CI)	Significance
Median HOAMS score	PHT	8	6	-2 (n/a)	0.497	3 (n/a)	0.200
	Surgery	6	7	1 (n/a)	0.238		
Mean Cartilage thickness/ mm	PHT	2.7	2.3	-0.4 (-0.11, 0.85)	0.116	0.03 (-0.52, 0.45)	0.877
	Surgery	2.5	2.2	-0.3 (-0.06, -0.59)	0.022*		

Missing data handled by listwise exclusion. n/a = not applicable. * statistically significant result with an alpha value of 0.05.

8.5 Discussion

8.5.1 Assessment of Feasibility

In this feasibility study my objectives were to:

- Assess recruitment and retention rates
- Assess the integrity of the proposed protocol
- Assess the feasibility of using the proposed outcomes measures.

By assessing these objectives I intended to inform the design of a full trial of whether surgery alters the natural history of cam and pincer morphology associated with FAI syndrome.

Recruitment and Retention

In judging whether it is feasible to conduct a full trial I need to consider a number of issues. Firstly is it feasible to randomise subjects into a clinical trial of surgery for FAI syndrome. This was demonstrated to be possible in previous research.^{7,297,318,319} I utilised these lessons when I recruited patients into the FASHIoN full trial and this study. In this study I demonstrated that 83% of participants would be willing to return to the hospital for additional imaging 12 months post treatment. This was lower than the follow up in the full UK FASHIoN trial (92%), however the burden on the patients was greater in this study. I required patients to attend hospital, thereby losing half a day of work and having to pay for transport and parking. It is also worth noting that patients recruited at UHCW were not just from local area. Many patients had to travel a number of hours to reach UHCW for follow up imaging. Both of these effects will have diminished the follow up rate. However 83% is in line with similar studies; Schmaranzer et al report a one year MRI follow up rate of 80% in their single centre case series.³²⁰

Protocol Integrity

An important function of feasibility studies is to determine how well the protocol functions.³¹⁰ This allows the opportunity to make alterations to the protocol before

a full trial, where issues that had not been anticipated are encountered.³¹⁰ One of the factors I had not anticipated, that would impact the ability to draw inferences from a full trial, is the time between baseline and follow up imaging. This differed between the treatment allocations, creating a confounding variable. This was primarily due to the length of the surgical waiting list. Having observed how long these delays were in this feasibility study I would want to amend the study design for a full trial so that baseline assessments, including T2* mapping, were recorded when treatment started (i.e. day of surgery or first PHT session). In this feasibility study with no dedicated funding I was unable to achieve this. Instead my plan (prior to the scanner being out of service) was to include the research sequences in the routine diagnostic scans that performed before randomisation. Fitting all required sequences, for both clinical assessment and research assessment, into a reasonable amount of time for the patient to tolerate on the MR scanner had already proved difficult. With sufficient funding I would separate research only scans to occur on the day treatment started. This would allow greater consistency in the time between baseline and 12 months post treatment assessments, which was absent in this feasibility study. This approach does create the potential for unmeasured differences between the groups to emerge between randomisation and treatment due to the differences in time to treatment. This may not be satisfactory in a pragmatic study, however I feel it is an acceptable trade off for an explanatory mechanistic trial.

In order to measure the efficacy of shape changing surgery to alter the natural history of FAI syndrome it is essential that the reshaping surgery is successful. Within UK FASHIoN a panel reviewed vignettes consisting of the operation notes, intra operative photographs and the post operative MRI scans.⁸⁰ The panel found that in 85% of cases included in this study the shape changing surgery was satisfactory. Across the UK FASHIoN trial, in all 24 centres, surgery was satisfactory in only 71% of cases. These effects are the reality of surgical care. Hip arthroscopy is technically challenging and surgeons may not achieve what they intended due to technical difficulties of the procedure. This pragmatic effect has the potential to undermine the results of an explanatory mechanistic trial. If the hypothesis for a full trial is that shape changing surgery alters the natural history

of FAI syndrome, the power of the study would be reduced if only 71% of subjects receive satisfactory shape changing surgery. A full explanatory trial would need to only include those surgeons who performed surgery to a high fidelity, whereas a pragmatic trial (such as UK FAHSIoN) looked to include all surgeons across the NHS.

Both of these proposed changes alter the balance between the degree of pragmatism and the explanatory nature of a full trials design.³²¹ UK FASHIoN was inherently pragmatic in its design, it intended to aid treatment *decision making*.³²¹ In the trial I am proposing I intend to *understand* whether treatment alters the natural history of FAI syndrome (and conversely whether the natural history of FAI syndrome *is* a deterioration in cartilage quality).³²¹ In posing a research question that is trying to understand a process, the trial's design is more explanatory in nature. Both the changes I have proposed in the protocol reflect this.

Use of proxy outcome measures

In assessing the feasibility of using T2* mapping as an outcome I encountered a number of difficulties. I had to redraw the ROI to avoid voxels with impossible values. Impossible values were encountered in voxels that the Functool software was unable to fit an exponential decay curve to the data. I noted these voxels were typically located at the junction of the subchondral bone and cartilage. It is difficult to understand why I encountered this issue. One possible explanation, which is in keeping with the location of these values, is the presence of susceptibility artefact.³⁰¹ Susceptibility artefacts cause more dephasing of the MR signal.³⁰⁵ They are caused by increased tissue heterogeneity, due to artificial particles such as air, implants and post surgical matter. They also occur at tissue interfaces such as the subchondral bone and cartilage.³⁰⁵ This may explain why I encountered impossible values at the subchondral junction as the voxel sampled tissues of two different T2* values.

The sensitivity of a sequence to susceptibility artefacts is increased by imaging with a larger FOV and therefore larger voxel size.³⁰⁵ In this study I used a relatively large field of view (180x180mm) compared to other studies of T2* mapping in the hip (see Table 41). This was so that the T2* sequences were matched in orientation to the morphological SPGR sequence. One of the uses of the SPGR sequence in this study was to assess, in patients allocated surgery, whether the shape had been sufficiently altered, this required a field of view that covered the entire hip joint. The surgical review panel assessed this information. When planning this study I had also intended to use the SPGR sequences to draw the ROI that would be used for the T2* mapping. Drawing the ROIs on SPGR sequences would also allow me to perform rigid registration (a technique to spatially align images obtained at different times).³²² This would ensure that the same ROI was being measured in the MRI scans before and after treatment. Given the changes I had to make to the feasibility study design, this feature was not required. However having a larger field of view did compromise the resolution and increased the voxels size. This may have increased the effect of the susceptibility artifact and prevented me from being able to measure the acetabular and femoral cartilage separately. To resolve this issue I would need to perform the T2* mapping using a smaller FOV. This would reduce the size of the voxels, so each voxel sampled less tissue. This would compromise the ability to perform rigid registration and draw the ROI in consistent places, in images obtained at different points in time.

Compared to other studies of T2* mapping of hip joint cartilage the values reported in this study were on average lower. Ellerman et al compared pre-operative T2* values to arthroscopic cartilage assessment. In macroscopically normal cartilage (Beck score 1) they reported a T2* value of 35.3 (SD7) with arthroscopically degenerate cartilage (Beck score 5 and 6) measuring 16.8ms (SD4).³⁰⁶ Bittersohl et al assessed femoral heads with T2* mapping followed by histological sections. Histologically normal cartilage (Mankin grade 0) had a T2* value of 36.3ms (SD4) while histologically degenerative cartilage (Mankin score 3) had a T2* value of 22.8ms (SD4.3).³⁰⁷ Bittersohl et al, in a further 2012 study, compared the T2* values in subjects with FAI syndrome and suspected cartilage injury to asymptomatic volunteers. They report that morphologically normal

cartilage on MRI (Outerbridge score 0) had a T2* value of 25.2ms compared to 18.1ms in Outerbridge 2.³²³ These studies all report different normative values, however their values for normal and abnormal cartilage were well above the mean values noted in this study. It is difficult to know whether the differences in the T2* values reported in this study and the literature are due to inherent differences in the patients, their treatments, the scanning protocols or the post acquisition processing. The PHT control group data reassures me that the low values are not a consequence of artifact from surgery. The scanning protocols and manufacturers do differ in this study (see Table 41); but that is to be expected.

Table 41 Comparison of Different T2* Scanning Protocols

Study	MRI Manufacturer	Plane	TR/ TE (ms)	Slices	Slice thickness (mm)	Resolution	Field of view/mm	Sequence time/min
This study	GE	Sagittal	39.48/ 1.8, 4.1, 6.5, 8.8, 11.2, 13.6, 15.9, 18.3, 20.6, 23.0, 25.3, 27.7, 30.0, 32.4, 34.7, 37.1	60	2.4	180/128 x 180/224	180x180	7
Ellerman et al 2014 ³⁰⁶	Siemens	Sagittal	1040/ 4.2, 11.3, 18.4, 25.6, 32.7	24	3	0.52x 0.52interpolated to 0.26x 0.26	NR	7
Apprigh et al 2012 ³²⁴	Siemens	Coronal and oblique	125/ 4.4, 8.5, 12.6, 16.7, 20.7, 24.8	NR	NR	NR	160x160	4
Bittersohl et al 2012 ³⁰⁷	Siemens	NR	38/ 4.6, 9.4, 15.2, 21.2, 27.0, 32.9	NR	0.6	0.6x0.6mm	192	13

In order to understand these differences I, and the MR physics department, performed three new analyses.

1. I compared T2* values of subjects treated with surgery, who had macroscopic evidence of cartilage degeneration to subjects with macroscopically normal cartilage.

I selected subjects who had undergone surgery and had an inspection of the articular surface. The patients were divided into 2 groups; those with International Cartilage Repair Society (ICRS) grade 3 or 4 chondral damage in any location (n=6) and those with grade 0-2 (n=7). There were minimal differences in the mean T2* values in the 8 different ROI; see Table 42. I have not reported statistical testing due to the high probability of both type 1 and type 2 errors. This suggests our T2* mapping is not sufficiently sensitive to detect changes in cartilage quality between

ICRS grade 0-2 and grades 3-4. Although it should be noted that the T2* mapping was performed 12 months after surgery. This is contrary to the research of Bittersohl et al who showed T2* could detect changes in different grades of cartilage degeneration.^{307,323}

Despite the support available to me in setting up T2* mapping at UHCW (CH, SW and VS) we were unable to replicate Bittersohl's results. This suggests that T2* mapping is insufficiently generalisable as a proxy outcome of cartilage degeneration to be used in multicenter research.

2. I compared T2* measures between all subjects with FAI syndrome and asymptomatic volunteers who were imaged in the development of the protocols.

Prior to the study commencing, in order to optimise the MR scanning sequences, a number of asymptomatic volunteers were imaged. I assessed whether the T2* value of asymptomatic volunteers was nearer the normal values reported in the literature; see Table 42. Despite the developmental work on the MR sequences (in the volunteer group) the T2* protocol used was the same in all subjects. The control subjects had T2* values higher than the study participants but still below what is reported as normal values in the literature. This suggests that there may be a systematic error in the imaging technique or processing that was leading to T2* values below what was anticipated. The T2* mapping does appear sensitive to subjects with FAI syndrome and asymptomatic controls.

Table 42 Sub group analysis of T2* values

Group	Mean T2* value/ ms (SD)							
	ROI 1	ROI 2	ROI 3	ROI 4	ROI 5	ROI 6	ROI 7	ROI 8
Surgical cases with grade 0-2 cartilage (n=6)	12.1 (2.2)	9.9 (3.2)	9.3 (3.7)	11.3 (5.5)	9.4 (2.4)	10.4 (2.3)	12.2 (2.3)	14.8 (4.8)
Surgical cases with grade 3-4 cartilage (n=7)	12.4 (4.3)	11.2 (2.0)	7.9 (1.6)	7.4 (1.6)	9.7 (3.6)	11.8 (5.9)	14.4 (6.5)	13.3 (3.0)
All trial patients (n=24)	12.5 (3.2)	11.1 (3.3)	10.3 (4.8)	10.3 (4.9)	11.3 (6.3)	12.5 (5.5)	14.3 (5.4)	14.3 (4.8)
Control subjects (n=4)	18.7 (3.8)	19.9 (5.5)	17.6 (5.3)	15.5 (4.5)	13.5 (1.5)	15.8 (2.5)	19.0 (3.1)	15.3 (2.5)

3. Imaging of phantoms with known $T2^*$ values to assess the reliability of the scanner and post image processing.

In order to understand these differences VS, an MRI physicist who helped me develop the protocols, independently conducted further studies. (*unpublished*) VS synthesised cryogels of a predictable $T2^*$ value and imaged them using the $T2^*$ protocols. VS performed three different experiments:

- a) VS manually plotted the raw data used to generate $T2^*$ maps, in order to assess how well the exponential curves used to calculate the $T2^*$ value fitted. This analysis was only possible using data generated in Osirix, as she could not extract the raw data in Functool.
- b) VS compared the $T2^*$ maps generated in Osirix and Functool (used in this study).
- c) VS compared the $T2^*$ maps generated using the body wrap coil (used in this study) and the knee coil (used in another study of knee cartilage).

In her report VS comments that in samples where there were significant discrepancies in the actual and the recorded $T2^*$ values, the software failed to accurately fit data to the exponential decay curve. In her comparisons between the different software available to calculate the $T2^*$ value, VS found that Functool (used in my study) performed better than Osirix. This may be due to the subjective manual correction for noise in Osirix (noise correction is automated in Functool).

VS also assessed the performance of the different coils. The data collected using the knee coil more accurately reflected the anticipated $T2^*$ of the cryogel than the body coil (used in this study). The body coil underestimated the $T2^*$ value. VS hypothesised that this may be due to the knee coil generating a more uniform radiofrequency field $B1$.

These three additional evaluations attempted to determine reasons why the $T2^*$ measurements did not perform well in this study. The evaluations identify hypotheses, which would need to be tested in more detail in further studies. A further potential cause that we were unable to assess was the affect of different MRI manufacturers. Our 3T MRI was manufactured by GE. Other research groups

whose protocols are listed in Table 41, and whose 'normative' I have quoted above, used MRI scanners manufactured by Siemens. It has been reported that there is poor inter device reliability in measures of cartilage T2 values between different manufacturers MRI scanners.³²⁵

The use of HOAMS and cartilage thickness as proxy outcome measures did not present as many issues of feasibility as T2* mapping. These measures did not require as much post imaging processing as T2* mapping. When using these outcomes it is difficult to assess what would constitute a clinically important change. T2* mapping has clinically relevant differences defined, by means of histological and macroscopic grading of cartilage.^{306,307}

Impact of UK FASHIoN trial

Buxton's law states "*its always to early (for rigorous evaluation) until, unfortunately its suddenly too late*".³²⁶ Applied to the surgical setting this law refers to how as a surgical technique becomes widely adopted, the surgeon equipoise is lost.

The equipoise of surgeons to participate in a RCT of FAI syndrome was assessed in the FASHIoN feasibility study.^{7,319} It was shown that surgeons were in sufficient equipoise to participate in a RCT comparing arthroscopic surgery and physiotherapy for FAI syndrome- this study was conducted in 2012. However any equipoise, and willingness to participate in research assessing the mechanistic effects of surgery on cartilage quality may be lost when the results of UK FASHIoN are revealed. UK FASHIoN reports an adjusted difference between PHT and surgery of 6.8 points (iHOT33; 95%CI 1.7, 12.0) in favour of surgery.³²⁷ It is possible the surgical community and patients will view this result as a justification for surgery. Conversely surgeons, patients and commissioners may prefer to treat FAI syndrome with PHT in view of the small benefit attributable to surgery (minimally clinically important difference of iHOT33 6.1points).²³² Further qualitative research would be necessary to assess surgeon and patient equipoise for an explanatory trial.

The other impact of the results of the UK FASHIoN trial may be a reluctance to fund and conduct further trials in the UK evaluating surgery and physiotherapy. I had anticipated this occurring when I planned this feasibility study. In planning an explanatory mechanistic trial of shape changing surgery a number of potential controls are available. These include no surgery (or physiotherapy), placebo surgery or active surgery of the central compartment (to treat labral tears etc) but no reshaping. The choice of which control arm to use is ultimately dictated by the research question. For my research question a trial with a control arm of arthroscopic surgery and no reshaping is best suited to determine the effect of shape changing surgery. Viewed from another perspective, this control assesses only the impact of cam or pincer morphology on the development of OA, and not other aspects of the surgical procedure.

A future trial of this design may also be of interest to funders, as it would evaluate the potential placebo effect of shape changing surgery. Placebo effects have been defined as 'any effect attributable to a pill, potion, or procedure, but not to its pharmacodynamic or specific properties'.³²⁸ In surgery placebo effects may be attributable to the surgical procedure or the personality of the surgeon and their team.³²⁹ The placebo effect of surgery can be large and is a potential explanation for the relatively modest effect size observed in UK FASHIoN.³³⁰ Trials of a similar design are already being conducted (FIRST trial NCT01623843 and HIPARTI trial NCT02692807), although they are not assessing the effects of surgery on the natural history of the disease.

Summary of feasibility assessment

In summary this feasibility study has demonstrated that it is possible to recruit and retain subjects to 12 months post treatment. It was reassuring that only 1 patient (4%) crossed over between allocations in the 12 month follow up period. The protocol for a full trial would need refining in order to limit differences in the interval between baseline and follow up imaging. The effectiveness of surgical reshaping does raise issues about the feasibility of a mechanistic trial. In a mechanistic trial all subjects would need to have satisfactory reshaping in order

that the outcomes of the trial could be attributed to the reshaping, but also to ensure the study is adequately powered.

The main issues with respect to feasibility revolve around the use of T2* mapping as an outcome. The issues of susceptibility artefact, reduced sensitivity of the measure and lower than reported normal values compromised the use of T2* mapping as a proxy marker of OA in this study. Minor changes to the imaging protocol such as reducing the field of view and using a different coil may reduce the impact of these factors. Further experiments on phantoms and volunteers would be required prior to using T2* measurements in a multicenter clinical trial.

Prior to any full trial further qualitative research would be required to understand patient and surgeon equipoise and willingness to conduct a mechanistic trial.

8.5.2 Other relevant research

In this study I was assessing the feasibility of a full trial. The hypothesis of a full trial is that shape-changing surgery alters the natural history of FAI syndrome. The mechanism through which this might occur is that by reshaping the hip the surgeon is able to prevent the premature contact between the proximal femur and acetabular rim that injures the acetabular cartilage.³² In cam type FAI syndrome this premature contact causes labral tears and cartilage delamination.³² By reshaping the head neck junction the repetitive injury to the acetabular labrum will theoretically cease preventing on-going injury to the labrum and cartilage; therefore slowing the progress of hip osteoarthritis. In pincer type FAI syndrome the premature contact between the acetabular rim and femoral neck causes a contre-coup injury to the posterior-inferior acetabular cartilage.³² This occurs as the femoral head is levered out of the acetabulum due to anterior pincer impingement. By reshaping the acetabular rim the surgeon intends that they can prevent anterior impingement that causes in the head to lever out of the acetabulum.

Other clinical trials are currently being conducted in the field of FAI syndrome evaluating a similar hypothesis. These include the FIRST trial and HIPARTI trials of surgery versus placebo surgery and mechanistic trials of surgery versus physiotherapy. The Australian FASHIoN and FAIT trials are using dGEMRIC analysis in their mechanistic studies, although the feasibility of using dGEMRIC in a RCT of FAI syndrome has not been reported.^{296,297}

Changes in cartilage quality have been assessed in patients undergoing different types of hip preservation surgery. Schmaranzer et al conducted a non-randomised trial comparing surgically and conservatively treated patients with FAI syndrome. At 12 months they report the dGEMRIC index in surgically treated patients deteriorated more than those treated conservatively.³²⁰ In a longitudinal study of patients who had undergone peri-acetabular osteotomy a decline in the dGEMRIC index at 12 months was followed by a slight recovery by 2 and 3 years.^{284,285} More recently Beaulé et al report a case series of 10 males who had undergone arthroscopic FAI surgery. They report an improvement in bone mineral density and T1rho signal at 2 year follow up, suggesting surgery offers a chondro-protective effect.²⁹³

8.6 Conclusion

In conclusion, at present, it is not feasible to undertake a full RCT assessing whether surgery alters the natural history of cam and pincer morphology associated with FAI syndrome, using T2* mapping as a proxy outcome. This is primarily due to the presence of impossible values in the selected ROI and inconsistencies in the T2* values compared to the literature. Further issues with conducting a mechanistic RCT of FAI syndrome include the quality of arthroscopic surgical hip reshaping and potential changes in equipoise following the results of UK FASHIoN.

8.7 Reflections

Through this thesis I have attempted to evaluate the epidemiology of FAI syndrome. The natural progression of my thesis was to answer the research questions of whether surgery alters the natural history of cam and pincer morphology associated with FAI syndrome. However, I recognised the difficulties in answering this research question. In order to understand these difficulties, the potential solutions and the methods by which I should answer this research question I chose to conduct a feasibility study. This approach is supported by the MRC's guide to assessing complex interventions, which surgery for FAI syndrome certainly is.³¹⁰

I am aware of on going research attempting to answer these research questions that hasn't built on feasibility and pilot studies. These studies have encountered difficulties in failing to use the correct imaging protocols, not being able to recruit patients, retain subjects and prevent crossovers. The issues I encountered in my feasibility study, despite the promising nature of the literature, justify conducting it.

When I considered evaluating proxy markers of joint degeneration in this study I initially needed to decide which marker to use. The most widely studied is dGEMRIC. In consultation with our local MR physics department we decided not to use dGEMRIC. There were concerns about the potential toxicity of the unbound gadolinium used in dGEMRIC. Others share these concerns; clinical trials using dGEMRIC have had to alter the contrast agent during the study (presently unreported) due to concerns about toxicity. Other concerns regarding dGEMRIC raised by the MR physicists were the repeatability of the measurements. They were concerned that that cardiac output, activity level and time delay between administration of the contrast and imaging would create variability in the dGEMRIC index. We therefore decided to assess a non-contrast proxy measure. Our local MR scanners are not capable of T1rho and T2 mapping had relatively long acquisition times. We therefore chose to evaluate T2. This has the theoretical advantages of T2 mapping, of assessing cartilage water content but also the anisotropy of the collagen fibres as it uses gradient rather than spin echo. The GRE sequences also have the advantage of shorter acquisition times.*

Prior to commencing this research I worked with the MR physicists to develop and refine the sequences we used. We also tested different software for building the T2 maps. I settled on using a hybrid between Functool to build the maps and Osirix to draw the ROI; this approach utilised the strengths of both software packages.*

It was incredibly frustrating that the MR scanner was upgraded just as I was about to start recruitment. Unfortunately, I was restricted in this project by the timelines of UK FASHIoN and my own PhD and so couldn't delay commencing the research until the new scanner was installed, vetted and available for research scanning. This was particularly frustrating as I had spent time with the MR physicists optimising the diagnostic scans we conducted at UHCW to be non-contrast and to include a T2 mapping sequence to suit my study design.*

At the time of writing this chapter, I recognised the deficiencies in my own note keeping. When I assessed the ROI T2 maps I failed to record the original mean T2* value before adjusting for impossible values. I also failed to record how many voxels needed excluding and their precise location. This information would have been useful to report to understand how frequently I encountered the issue. Anecdotally I estimate I encountered an impossible value at least once in every two ROI. I also perceived the issue was greater in some patients and ROI than others.*

This chapter has provided an opportunity for me to understand the different nuances in the design of RCTs. When considering the design of a full trial I need to decide on the balance between explanatory and pragmatic trials. UK FASHIoN was a trial of a pragmatic design. It was assessing the effectiveness of a surgical treatment strategy versus non operative care across the NHS, reflecting the normal challenges of these patients in day to day clinical practice.³³¹ Explanatory trials typically intend to assess patients in ideal circumstances. For example; what is the effect of surgery if performed on carefully selected patients by the most experienced clinicians. The PRECIS tool was developed to aid researchers planning trials in order to develop a trial design that matches how the trials results are intended to be used.^{332,333} Ultimately the balance between explanatory and pragmatic trial design is dependent on the research question. The full trial that I propose is more explanatory in nature

than UK FASHIoN. To determine whether shape changing surgery alters the natural history of cam and pincer morphology associated with FAI syndrome, I would require carefully selected subjects, where over diagnosis is not present, and selected surgeons, who are the most effective and consistent in reshaping the hip.

The knowledge I have gained through this chapter into the design of RCTs has been supplemented by the work I have done over the last three years on UK FASHIoN. This has allowed me to understand the process of fully evaluating an intervention in a multicenter setting. Working as part of a team on UK FASHIoN, I had to identify and set up sites, train research staff, recruit and manage patients, contribute to the trials management meetings, help with planning the study analysis, interpreting the results and writing the manuscript. This was a fantastic opportunity to learn and understand how to run a challenging, large, multicentre RCT.

Through this chapter's research I have learnt the importance of feasibility studies. A feasibility study should be designed robustly to address the issues that may be encountered in a full study. This study was able to address the concern regarding the feasibility of using T2 mapping as a proxy marker of OA in a RCT.*

In summary, this chapter has allowed me to develop an understanding of the development of complex interventions from their background theory to full evaluation. I have had to develop an understanding of the nuances in different designs of RCTs and how design affects the trial's conduct and results. This learning has been supported by what I've gained from working with a team on UK FASHIoN trial.

9 Discussion and Conclusions

9.1 Review of thesis objectives

In this thesis I set out to explore the epidemiology of FAI syndrome. The aims of the thesis were to:

- Systematically review the current epidemiological evidence to determine the prevalence of cam and pincer morphology.
- Define FAI syndrome, its diagnostic criteria and how cam and pincer morphology should be measured, describing the diagnostic utility of those measurements.
- Establish the prevalence of cam and pincer morphology in the general population and in a population of elite athletes.
- Systematically review the evidence that demonstrates whether FAI causes hip OA.
- Evaluate a method to assess changes in surrogate markers of hip OA in the setting of a RCT.

9.2 Summary of new findings

In chapter 3 I used consensus development methodology to answer some fundamental questions regarding FAI syndrome. We gathered multidisciplinary experts from around the world with an interest in researching and treating FAI syndrome. The panel attended an open meeting and then discussed a number of research questions in a consensus conference I chaired. The publication that followed ‘The Warwick Agreement’, defined FAI syndrome and how it should be diagnosed.⁷⁰

As FAI syndrome is characterised by certain hip morphology I wanted to establish the point prevalence of these hip shapes in the population. In chapter 2 I attempted to define the prevalence of cam and pincer morphology in the general population and in sub groups of athletes. I identified a number of studies that reported the

prevalence, however none were truly general population based. I couldn't conduct a meta-analysis due to the lack of general population based studies and the methodological heterogeneity of the included studies. There was also heterogeneity of measures used to define cam and pincer morphology. There seemed little justification for the use of the different measures of cam and pincer morphology. I therefore sought to evaluate how best to define cam and pincer morphology. This issue was discussed in Chapter 3, but a consensus could not be reached.

In chapter 4 I conducted a study to determine the optimal methods of defining cam and pincer morphology associated with FAI syndrome. While the diagnostic criteria developed for cam morphology had an acceptable utility the criteria for pincer morphology did not display robust characteristics. The criteria I defined in chapter 4 to identify cam and pincer morphology, were different to those used to define cam and pincer morphology as a risk factor for OA.^{85,253,334 251} This maybe because differing degrees of cam or pincer morphology cause FAI and OA; for example a small cam may cause FAI syndrome but not OA. Alternatively it may reflect the possibility that FAI syndrome was being over diagnosed in the population of 'cases' I identified (false positives).^{84,89}

Having established how cam morphology should be defined I was able assess the point prevalence of cam morphology in the population. In Chapter 5 I applied the definitions established in Chapter 4, to a cross sectional sample that was broadly representative of the UK general population. I reported that the prevalence of cam morphology was 41%, with 51% of men and 30% of women affected. The prevalence of cam morphology, excluding subjects with evidence of hip OA, was 35% (males 44%, females 26%).

A number of studies identified in chapter 2 had suggested there was a higher prevalence of cam morphology in elite athletes compared to the general population. I therefore applied the definitions reported in chapter 4 to a selection of elite athletes. In chapter 6 I studied a group of elite male golfers. While I was unable to demonstrate a difference in the prevalence of cam morphology

compared to the general population, I did show that golfers had different hip shapes between their lead and trail hips. In a multiple linear regression I was able to demonstrate that increasing α angles and SEAs in golfers were associated with reduced hip related quality of life.

The next step in understanding the epidemiology of FAI syndrome is to define the relationship between cam morphology, pincer morphology and FAI syndrome, and the development of OA. In chapter 7 I evaluated the evidence of this relationship. I used the Bradford Hill criteria to assess each of these associations with hip OA. I identified sufficient evidence to suggest that cam morphology causes hip OA. There was very little evidence assessing the association between FAI syndrome (cam or pincer type) and hip OA, while the evidence that pincer morphology caused OA was equivocal. There was presently no evidence to fulfil the Bradford Hill criteria of experimental studies.

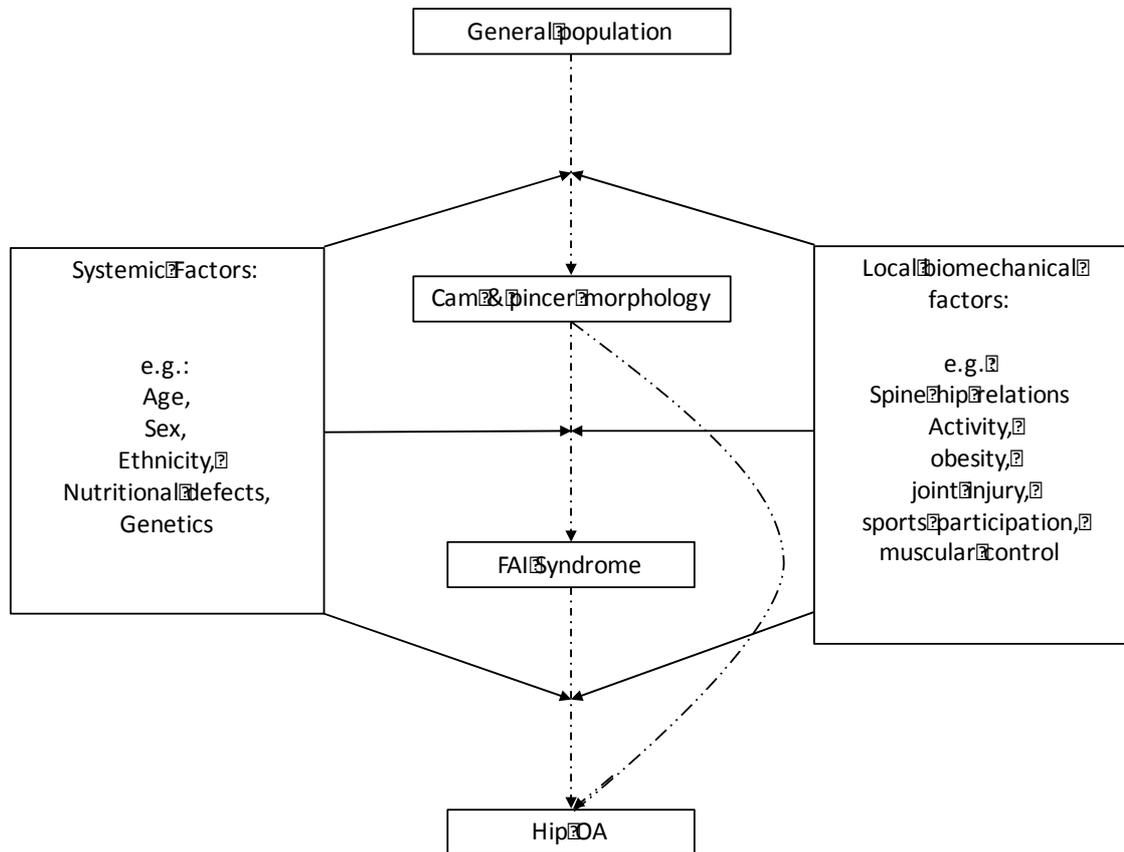
An experimental study would provide the strongest evidence of the relationship between FAI syndrome and OA. This study would also demonstrate whether surgery for FAI syndrome is able to alter the natural history of the disorder. In chapter 8 I conducted a feasibility study, to see if it was possible to perform a full trial assessing whether surgical treatment for FAI syndrome could alter the natural history of the disorder. In this study I assessed the feasibility of using T2* mapping as a proxy marker of hip OA. We were unable to replicate previous work assessing T2* mapping in the hip. The results of this study suggest that at present T2* mapping is not a sufficiently generalisable technique to be used as a proxy marker of OA in a full RCT. I suggest further evaluations that we could conduct in order to improve the validity and reliability of the measure when used at our institution.

9.3 New findings in the context of our present understanding and on-going research

In order to understand how my new findings fit in the context of wider research, I have developed a model that describes the epidemiology of FAI syndrome; see

Figure 54. The research I have conducted in this thesis has attempted to understand certain aspects of this model. But what other research has been published or is being conducted, that is relevant to this model of FAI syndrome?

Figure 54 Relationship between cam and pincer morphology, FAI syndrome and hip OA.



In Figure 54 I show a link between the general population and subjects with cam and pincer morphology. Possible reasons for the development of cam and pincer morphology are also displayed. Present research has hypothesised that cam morphology develops due to systemic and local biomechanical factors. Agricola et al reported that cam morphology developed in subjects during adolescence up to the closure of the proximal femoral physis.⁸⁶ Palmer et al, reported the same effect, demonstrating a doses response relationship between the degree of physical activity and the development of cam hip morphology.³³⁵ A finite element model conducted by Roels et al supported these findings, they showed that the development of cam morphology is directly associated with physical activity undertaken before the closure of the physis.⁸⁷ A genetic predisposition to the

development of cam morphology has also been reported. In the Sibkids cohort (described in Chapter 7) Pollard et al report an odd ratio of developing cam morphology of 2.1 in siblings compared to controls.²⁵⁰ Despite various studies reporting the environmental and genetic factors that predispose to the development of cam morphology, little is understood about the development of pincer morphology. Some authors even consider that pincer morphology causes a completely separate disorder to cam type FAI syndrome.^{336,337}

Understanding why some subjects with cam or pincer morphology develop FAI syndrome remains challenging. There do seem to be certain systemic and local biomechanical factors, as my model implies. The SibKids cohort suggests that siblings with a family history of OA were more likely to develop pain in the presence of cam and pincer morphology than controls, suggesting a possible genetic association with the development of FAI syndrome.²⁵⁰ The role of activity levels in the development of FAI syndrome is unclear partly due to the prevalence of FAI syndrome in athletic subjects and controls being unknown. It does appear that hip muscle control may affect the development of FAI syndrome. Subjects with FAI syndrome have been reported to have reduced hip muscle power and altered movement patterns, although the temporality of these factors is not known.^{53,54,76,338} The effect of an unfavourable combination of morphology (including femoral neck antetorsion) and the degree of motion remains the best understood, and most studied cause of FAI syndrome. More recently research has focused on the relationship between the spine and hip. Weinberg et al assessed the pelvic incidence in subjects with FAI syndrome and controls and reported that subjects with FAI syndrome had a reduced pelvic incidence.⁵² It is hypothesised that a reduced pelvic incidence reduces the ability of the pelvis to posteriorly tilt, a movement pattern that might alleviate anterior impingement.⁵¹

Until recently there has been uncertainty about the most effective method of managing patients with FAI syndrome.^{70,150} As I explained in my introduction, while conducting my PhD research I have been working as a research fellow on the UK FASHIoN trial.⁸⁰ This is the largest multi centre RCT assessing physiotherapy led rehabilitation and arthroscopic surgery. The trials results demonstrate a

statistically and clinically significant benefit of surgery compared to best conservative care.³²⁷ Other RCTs are also been conducted but are yet to report their results. These include the Aus FASHIoN, US Military Health Service and the FAIT trials comparing arthroscopic surgery to physiotherapy, and the FIRST and HIPARTI trials, comparing arthroscopic surgery to placebo surgery.⁷⁰

In chapter 7 I summarise the present research that demonstrates an association between cam and pincer morphology and FAI syndrome and OA. I am aware that a number of studies are ongoing that are attempting to assess if surgery can reduce the progression to OA. The Aus FASHIoN and FAIT RCTs, the comparative non controlled study from Bern and a case series from the Ottawa group, are presently using dGEMRIC to evaluate the effect of surgery on cartilage.^{320 293,296,297} If these studies were to demonstrate that FAI surgery was chondro-protective how might this affect patients?

Currently, only symptomatic patients present to surgical outpatient clinics. We now have level one evidence that shows surgery in patients with FAI syndrome, improves hip related quality of life. To treat asymptomatic cam morphology, in order to reduce the onset of OA, would require a screening programme. With such a high prevalence of cam morphology, as reported in Chapter 5, offering surgery to all subject with cam morphology would be inappropriate. Furthermore, the success of surgery, even in those with FAI syndrome, is not a forgone conclusion. Putting an asymptomatic patient through surgery risks them getting a complication and ending up worse than before. Therefore, even if there were evidence that surgery was chondro-protective, as a community I do not believe we should not embark on treating asymptomatic hips. This is consistent with the consensus statement in Chapter 3.⁷⁰

9.4 Future Research

Figure 54 also provides a stimulus to identify areas for future research that follow work that I have achieved in this thesis. Future research includes:

- Establishing the point prevalence of FAI syndrome
- A RCT to determine whether surgical intervention alters the natural history of FAI syndrome
- Identify the modifiable and non-modifiable risk factors for the development of cam and pincer morphology, FAI syndrome and OA secondary to FAI syndrome.

In the consensus development conference presented in Chapter 3 the open meeting members proposed research questions that they felt it were important to answer. The consensus panel members then ranked these research questions in terms of their importance; see Table 43. Many of the future research questions that I have identified feature highly.

Table 43 Future Research Questions and their rank by the panel of the “2016 Warwick Agreement”

Research Question	Rank
In those with FAI morphology, can we predict who will become symptomatic?	1
Is surgery or conservative management more effective for improving short- and long-term outcomes?	2
What is the outcome of conservative treatment?	3
Is FAI surgery more effective than sham surgery?	4
How do we define FAI syndrome?	5
What is the natural history of FAI morphology?	6
Which patients respond best to conservative management?	7
What is the most effective conservative management program?	8
Do changes to training in adolescent athletes decrease cam formation?	9
What is the role of hip muscle dysfunction and movement patterns in FAI morphology and symptoms?	10
Can rehabilitation prevent FAI pain and if so, how?	11
What are the diagnostic criteria for Cam and Pincer morphology?	12
What is the source of pain in FAI?	13
Does operating on asymptomatic hips lead to long-term benefits in terms of reducing OA?	14
What is the incidence and prevalence of FAI syndrome?	15
What are the best outcome measures to show change following treatment?	16
What is the role of structural features in FAI syndrome eg. Femoral anteversion, capsular tightness?	17
What is the optimal post operative rehabilitation program?	18
What is the optimal method to treat labral pathology?	19
Which factors affect surgical outcomes eg. pre-and post-op alpha angle, fem retroversion, age, sex, OA?	20
Does pre-operative rehabilitation improve post-operative outcomes?	21

What are the return to sport criteria following FAI surgery?	22
Does capsule closure lead to improved patient outcomes?	23

As I enter the final stages of my PhD training I am now considering addressing some of these research questions. I would like to be able to estimate the prevalence of FAI syndrome and better define the natural history of the disorder. I am planning on using an existing research collaboration to interrogate data held within a general population based cohort study.^{224,339} I am aware that this dormant cohort study, which enrolled subjects in the 1990s, has data reporting patients hip symptoms, a comprehensive clinical examination and AP radiographs. This may be sufficient to estimate the prevalence of FAI syndrome at a time prior to the disorder being widely recognised and treated. As patients would not have been diagnosed and treated in the 1990s, I hope that by examining the cohort study records I could estimate the point prevalence of FAI syndrome.

This same cohort study data could also be used to establish the natural history of untreated FAI syndrome. This information could be sought by a follow up assessment of subjects identified as having FAI syndrome, or by linking to the National Joint Registry to determine how many subjects required hip arthroplasty. I am currently developing this research plan and have been awarded a grant to support another researcher to conduct this work.

Through my PhD training I have worked on the UK FASHIoN trial. We now are in a position to report the results of the trial. While surgery was shown to be superior on average, the range of surgical outcomes (iHOT-33 scores of 0-100), suggest surgeons and patients need more information to choose the most appropriate treatment.

This work will ultimately rely on a deep understanding of the epidemiology of FAI syndrome. It is only by truly understanding the epidemiology of FAI syndrome that we can select the most appropriate treatment for each individual patient. Through this thesis I have attempted to make a significant contribution to the literature in

this area. I now look to applying this new knowledge and my research training to improve patient care.

10 References

1. Standring S. Gray's Anatomy: The Anatomical Basis of Clinical Practice: Churchill Livingstone/Elsevier; 2008.
2. Troum OM, Crues III JV. The young adult with hip pain: diagnosis and medical treatment, circa 2004. *Clinical orthopaedics and related research* 2004; **418**: 9-17.
3. Smith-Petersen M. Treatment of malum coxae senilis, old slipped upper femoral epiphysis, intrapelvic protrusion of the acetabulum, and coxa plana by means of acetabuloplasty. *Journal of Bone & Joint Surgery - American Volume* 1936; **18**(4): 869-80.
4. Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clinical orthopaedics and related research* 2003; **417**: 112-20.
5. Colvin AC, Harrast J, Harner C. Trends in hip arthroscopy. *Journal of Bone & Joint Surgery - American Volume* 2012; **94**(4): e23.
6. Montgomery SR, Ngo SS, Hobson T, et al. Trends and demographics in hip arthroscopy in the United States. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2013; **29**(4): 661-5.
7. Griffin DR, Wall PD, Realpe A, et al. UK FASHIoN: Feasibility study of a randomised controlled trial of arthroscopic surgery for hip impingement compared with best conservative care. *Health Technology Assessment* 2016; **20**(32).
8. Martin HD, Kelly BT, Leunig M, et al. The pattern and technique in the clinical evaluation of the adult hip: the common physical examination tests of hip specialists. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2010; **26**(2): 161-72.
9. Toogood PA, Skalak A, Cooperman DR. Proximal femoral anatomy in the normal human population. *Clinical orthopaedics and related research* 2009; **467**(4): 876.
10. Yoshioka Y, Siu D, Cooke T. The anatomy and functional axes of the femur. *The Journal of bone and joint surgery American volume* 1987; **69**(6): 873-80.
11. Hogervorst T, Bouma H, De Boer S, De Vos J. Human hip impingement morphology: an evolutionary explanation. *The Journal of bone and joint surgery British volume* 2011; **93**(6): 769-76.
12. Eijer H, Leunig M, Mahomed M, Ganz R. Cross-table lateral radiographs for screening of anterior femoral head-neck offset in patients with femoro-acetabular impingement. *Hip International* 2001; **11**: 37-41.
13. Vandenbussche E, Saffarini M, Delogé N, Moctezuma J-L, Nogler M. Hemispheric cups do not reproduce acetabular rim morphology. *Acta orthopaedica* 2007; **78**(3): 327-32.
14. Cobb J, Logishetty K, Davda K, Iranpour F. Cams and pincer impingement are distinct, not mixed: the acetabular pathomorphology of femoroacetabular impingement. *Clinical Orthopaedics and Related Research*® 2010; **468**(8): 2143-51.
15. Vandenbussche E, Saffarini M, Taillieu F, Mutschler C. The asymmetric profile of the acetabulum. *Clinical orthopaedics and related research* 2008; **466**(2): 417-23.

16. Pfirrmann CW, Mengiardi B, Dora C, Kalberer F, Zanetti M, Hodler J. Cam and pincer femoroacetabular impingement: characteristic MR arthrographic findings in 50 patients. *Radiology-Radiological Society of North America* 2006; **240**(3): 778-85.
17. Beck M, Leunig M, Ellis T, Sledge J, Ganz R. The acetabular blood supply: implications for periacetabular osteotomies. *Surgical and Radiologic Anatomy* 2003; **25**(5-6): 361-7.
18. Dandachli W, Nakhla A, Iranpour F, Kannan V, Cobb JP. Can the acetabular position be derived from a pelvic frame of reference? *Clinical orthopaedics and related research* 2009; **467**(4): 886-93.
19. Murray D. The definition and measurement of acetabular orientation. *The Journal of bone and joint surgery British volume* 1993; **75**(2): 228-32.
20. Siebenrock K, Kalbermatten D, Ganz R. Effect of pelvic tilt on acetabular retroversion: a study of pelves from cadavers. *Clinical Orthopaedics and Related Research* 2003; **407**: 241-8.
21. Legaye J, Duval-Beaupere G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *European Spine Journal* 1998; **7**(2): 99-103.
22. Boulay C, Tardieu C, Hecquet J, et al. Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis. *European Spine Journal* 2006; **15**(4): 415-22.
23. Duval-Beaupere G, Schmidt C, Cosson P. A Barycentremetric study of the sagittal shape of spine and pelvis: the conditions required for an economic standing position. *Annals of biomedical engineering* 1992; **20**(4): 451-62.
24. Junqueira LCU, Carneiro J. Basic Histology: Text & Atlas: Lange Medical Books, McGraw-Hill, Medical Pub. Division; 2003.
25. Buckwalter J, Mankin H. Instructional Course Lectures, The American Academy of Orthopaedic Surgeons-Articular Cartilage. Part I: Tissue Design and Chondrocyte-Matrix Interactions*†. *Journal of Bone & Joint Surgery - American Volume* 1997; **79**(4): 600-11.
26. Steward AJ, Liu Y, Wagner DR. Engineering cell attachments to scaffolds in cartilage tissue engineering. *The Journal of The Minerals, Metals & Materials Society* 2011; **63**(4): 74-82.
27. Seldes RM, Tan V, Hunt J, Katz M, Winiarsky R, Fitzgerald Jr RH. Anatomy, histologic features, and vascularity of the adult acetabular labrum. *Clinical orthopaedics and related research* 2001; **382**: 232-40.
28. Ferguson S, Bryant J, Ganz R, Ito K. The acetabular labrum seal: a poroelastic finite element model. *Clinical Biomechanics* 2000; **15**(6): 463-8.
29. Konrath GA, Hamel AJ, Olson SA, Bay B, Sharkey NA. The Role of the Acetabular Labrum and the Transverse Acetabular Ligament in Load Transmission in the Hip*. *Journal of Bone & Joint Surgery - American Volume* 1998; **80**(12): 1781-8.
30. Stanley D. Advanced examination techniques in Orthopaedics: Cambridge University Press; 2002.
31. Loubert PV, Zipple JT, Klobucher MJ, Marquardt ED, Opolka MJ. In vivo ultrasound measurement of posterior femoral glide during hip joint mobilization in healthy college students. *Journal of Orthopaedic & Sports Physical Therapy* 2013; **43**(8): 534-41.

32. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage femoroacetabular impingement as a cause of osteoarthritis of the hip. *Journal of Bone & Joint Surgery - British Volume* 2005; **87**(7): 1012-8.
33. Kolo FC, Charbonnier C, Pfirrmann CW, et al. Extreme hip motion in professional ballet dancers: dynamic and morphological evaluation based on magnetic resonance imaging. *Skeletal radiology* 2013; **42**(5): 689-98.
34. Conditions NCCfC, Excellence NIfC. Osteoarthritis: national clinical guidelines for care and management in adults. Royal College of Physicians; 2008.
35. Excellence NIOHaC. Osteoarthritis: care and management. *NICE guidelines [CG177]* 2014.
36. Altman R, Alarcon G, Appelrouth D, et al. The American College of Rheumatology criteria for the classification and reporting of osteoarthritis of the hip. *Arthritis & Rheumatology* 1991; **34**(5): 505-14.
37. Arden N, Nevitt MC. Osteoarthritis: epidemiology. *Best practice & research Clinical rheumatology* 2006; **20**(1): 3-25.
38. Kellgren J, Lawrence J. Radiological assessment of osteo-arthrosis. *Annals of the rheumatic diseases* 1957; **16**(4): 494.
39. Tönnis D, Heinecke A. Current Concepts Review-Acetabular and Femoral Anteversion: Relationship with Osteoarthritis of the Hip. *Journal of Bone & Joint Surgery - American Volume* 1999; **81**(12): 1747-70.
40. Oliveria SA, Felson DT, Reed JI, Cirillo PA, Walker AM. Incidence of symptomatic hand, hip, and knee osteoarthritis among patients in a health maintenance organization. *Arthritis & Rheumatology* 1995; **38**(8): 1134-41.
41. Registry NJ. The 14th Annual Report National Joint Registry for England, Wales, Northern Ireland and the Isle of Man, 2017.
42. Dieppe PA, Lohmander LS. Pathogenesis and management of pain in osteoarthritis. *The Lancet* 2005; **365**(9463): 965-73.
43. Felson DT, Lawrence RC, Dieppe PA, et al. Osteoarthritis: new insights. Part 1: the disease and its risk factors. *Annals of internal medicine* 2000; **133**(8): 635-46.
44. Dieppe P. The classification and diagnosis of osteoarthritis. *Osteoarthritic disorders* 1995: 5-12.
45. Tannast M, Siebenrock KA, Anderson SE. Femoroacetabular impingement: radiographic diagnosis—what the radiologist should know. *American Journal of Roentgenology* 2007; **188**(6): 1540-52.
46. Sutter R, Dietrich TJ, Zingg PO, Pfirrmann CW. Femoral antetorsion: comparing asymptomatic volunteers and patients with femoroacetabular impingement. *Radiology* 2012; **263**(2): 475-83.
47. Ganz R, Gill T, Gautier E, Ganz K, Krügel N, Berlemann U. Surgical dislocation of the adult hip. *Bone & Joint Journal* 2001; **83**(8): 1119-24.
48. Murray R. The aetiology of primary osteoarthritis of the hip. *The British journal of radiology* 1965; **38**(455): 810-24.
49. Stulberg SD, Cordell LD, Harris W, Ramsey P, MacEwen G. Unrecognized childhood hip disease: a major cause of idiopathic osteoarthritis of the hip. The Hip: Proceedings of the Third Open Scientific Meeting of the Hip Society St Louis, MO: CV Mosby; 1975; 1975. p. 212-28.
50. Harris WH. Etiology of osteoarthritis of the hip. *Clinical orthopaedics and related research* 1986; **213**: 20-33.

51. Gebhart JJ, Streit JJ, Bedi A, Bush-Joseph CA, Nho SJ, Salata MJ. Correlation of pelvic incidence with cam and pincer lesions. *The American journal of sports medicine* 2014; **42**(11): 2649-53.
52. Weinberg DS, Gebhart JJ, Liu RW, Salata MJ. Radiographic signs of femoroacetabular impingement are associated with decreased pelvic incidence. *Arthroscopy : the journal of arthroscopic & related surgery : official publication of the Arthroscopy Association of North America and the International Arthroscopy Association* 2016; **32**(5): 806-13.
53. Kennedy M, Lamontagne M, Beaulé P. The effect of cam femoroacetabular impingement on hip maximal dynamic range of motion. *Journal of Orthopedics* 2009; **1**(1): 41-50.
54. Kennedy MJ, Lamontagne M, Beaulé PE. Femoroacetabular impingement alters hip and pelvic biomechanics during gait: walking biomechanics of FAI. *Gait & posture* 2009; **30**(1): 41-4.
55. Lamontagne M, Kennedy MJ, Beaulé PE. The effect of cam FAI on hip and pelvic motion during maximum squat. *Clinical orthopaedics and related research* 2009; **467**(3): 645-50.
56. Rylander J, Shu B, Favre J, Safran M, Andriacchi T. Functional testing provides unique insights into the pathomechanics of femoroacetabular impingement and an objective basis for evaluating treatment outcome. *Journal of Orthopaedic Research* 2013; **31**(9): 1461-8.
57. Ng KG, Lamontagne M, Adamczyk AP, Rahkka KS, Beaulé PE. Patient-specific anatomical and functional parameters provide new insights into the pathomechanism of cam FAI. *Clinical Orthopaedics and Related Research*® 2015; **473**(4): 1289-96.
58. Clohisy JC, Carlisle JC, Beaulé PE, et al. A systematic approach to the plain radiographic evaluation of the young adult hip. *Journal of Bone & Joint Surgery - American Volume* 2008; **90**(Supplement_4): 47-66.
59. Dunn D, Notley B. Anteversion of the neck of the femur: a method of measurement. *The Journal of bone and joint surgery British volume* 1952; **34**(2): 181-6.
60. Clohisy JC, Nunley RM, Otto RJ, Schoenecker PL. The frog-leg lateral radiograph accurately visualized hip cam impingement abnormalities. *Clinical Orthopaedics and Related Research*® 2007; **462**: 115-21.
61. Nepple JJ, Prather H, Trousdale RT, et al. Diagnostic imaging of femoroacetabular impingement. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**(suppl): S20-S6.
62. Nötzli H, Wyss T, Stoecklin C, Schmid M, Treiber K, Hodler J. The contour of the femoral head-neck junction as a predictor for the risk of anterior impingement. *Bone & Joint Journal* 2002; **84**(4): 556-60.
63. Gosvig K, Jacobsen S, Palm H, Sonne-Holm S, Magnusson E. A new radiological index for assessing asphericity of the femoral head in cam impingement. *Journal of Bone & Joint Surgery - British Volume* 2007; **89**(10): 1309-16.
64. Tönnis D, Legal H, Graf R, Telger TC. Congenital dysplasia and dislocation of the hip in children and adults: Springer-Verlag Berlin.; 1987.
65. Wiberg G. Shelf operation in congenital dysplasia of the acetabulum and in subluxation and dislocation of the hip. *Journal of Bone & Joint Surgery - American Volume* 1953; **35**(1): 65-80.

66. Reynolds D, Lucas J, Klaue K. Retroversion of the acetabulum: a cause of hip pain. *The Journal of bone and joint surgery British volume* 1999; **81**(2): 281-8.
67. Wiberg G. Studies on dysplastic acetabula and congenital subluxation of the hip joint: With special reference to the complication of osteoarthritis. *Acta chirurgica Scandinavica* 1939; **58**(5): 135.
68. Steppacher SD, Anwander H, Zurmühle CA, Tannast M, Siebenrock KA. Eighty percent of patients with surgical hip dislocation for femoroacetabular impingement have a good clinical result without osteoarthritis progression at 10 years. *Clinical orthopaedics and related research* 2015; **473**(4): 1333-41.
69. Philippon M, Briggs K, Yen Y-M, Kuppersmith D. Outcomes following hip arthroscopy for femoroacetabular impingement with associated chondrolabral dysfunction. Minimum two years follow up. *Journal of Bone & Joint Surgery - British Volume* 2009; **91**(1): 16-23.
70. Griffin DR, Dickenson EJ, Agricola R, et al. The 2016 Warwick Agreement on Femoroacetabular Impingement. *British journal of sports medicine* 2016; **50**(19): 1169-76.
71. Wall PD, Fernandez M, Griffin DR, Foster NE. Nonoperative treatment for femoroacetabular impingement: a systematic review of the literature. *PM&R* 2013; **5**(5): 418-26.
72. Diamond LE, Dobson FL, Bennell KL, Wrigley TV, Hodges PW, Hinman RS. Physical impairments and activity limitations in people with femoroacetabular impingement: a systematic review. *British journal of sports medicine* 2014; **49**(4): 230-42.
73. Casartelli NC, Maffiuletti NA, Bizzini M, Kelly BT, Naal FD, Leunig M. The management of symptomatic femoroacetabular impingement: what is the rationale for non-surgical treatment? *British journal of sports medicine* 2016; **50**(9): 511-2.
74. Wall PD, EJ; Robinson, D; Hughes, I; Realpe, A; Hobson, R; Griffin, DR; Foster, NE. Conservative Treatment for Femoroacetabular Impingement Syndrome: Personalised Hip Therapy and the FASHIoN Trial. *British journal of sports medicine* 2016; **50**(19): 1217-23.
75. Botha N, Warner M, Gimpel M, Mottram S, Comerford M, Stokes M. Movement patterns during a small knee bend test in academy footballers with femoroacetabular impingement (FAI). *Health Sciences Working Papers* 2014; **1**(10): 1-24.
76. Casartelli N, Maffiuletti N, Item-Glatthorn J, et al. Hip muscle weakness in patients with symptomatic femoroacetabular impingement. *Osteoarthritis and Cartilage* 2011; **19**(7): 816-21.
77. Ganz R, Klaue K, Vinh TS, Mast JW. A New Periacetabular Osteotomy for the Treatment of Hip Dysplasias Technique and Preliminary Results. *Clinical orthopaedics and related research* 1988; **232**: 26-36.
78. Parry JA, Swann RP, Erickson JA, Peters CL, Trousdale RT, Sierra RJ. Midterm outcomes of reverse (anteverting) periacetabular osteotomy in patients with hip impingement secondary to acetabular retroversion. *American Journal of Sports Medicine* 2016; **44**(3): 672-6.
79. Sampson TG. Arthroscopic treatment of femoroacetabular impingement. *Techniques in Orthopaedics* 2005; **20**(1): 56-62.
80. Griffin DR, Dickenson EJ, Wall PD, et al. Protocol for a multi-centre, parallel-arm, 12-month, randomised controlled trial of arthroscopic surgery versus

- conservative care for femoroacetabular impingement syndrome (FASHIoN). *BMJ Open* 2016; **6**(8): e012453.
81. Wall PDH. Treatments for Femoroacetabular Impingement University of Warwick University of Warwick 2013.
 82. Nepple JJ, Brophy RH, Matava MJ, Wright RW, Clohisy JC. Radiographic findings of femoroacetabular impingement in National Football League Combine athletes undergoing radiographs for previous hip or groin pain. *Arthroscopy - Journal of Arthroscopic and Related Surgery* 2012; **28**(10): 1396-403.
 83. Frank JM, Harris JD, Erickson BJ, et al. Prevalence of Femoroacetabular Impingement Imaging Findings in Asymptomatic Volunteers: A Systematic Review. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2015; **31**(6): 1199-204.
 84. Carter SM. Overdiagnosis, ethics, and trolley problems: why factors other than outcomes matter. *BMJ* 2017; **358**: j3872.
 85. Agricola R, Bessems JH, Ginai AZ, et al. The development of Cam-type deformity in adolescent and young male soccer players. *American Journal of Sports Medicine* 2012; **40**(5): 1099-106.
 86. Agricola R, Heijboer MP, Ginai AZ, et al. A cam deformity is gradually acquired during skeletal maturation in adolescent and young male soccer players: a prospective study with minimum 2-year follow-up. *American Journal of Sports Medicine* 2014; **42**(4): 798-806.
 87. Roels P, Agricola R, Oei E, Weinans H, Campoli G, Zadpoor A. Mechanical factors explain development of cam-type deformity. *Osteoarthritis and Cartilage* 2014; **22**(12): 2074-82.
 88. Sallis JF, Prochaska JJ, Taylor WC. A review of correlates of physical activity of children and adolescents. *Medicine & science in sports & exercise* 2000; **32**(5): 963-75.
 89. Moynihan R, Doust J, Henry D. Preventing overdiagnosis: how to stop harming the healthy. *BMJ* 2012; **344**: e3502.
 90. Borenstein DG, O'mara JW, Boden SD, et al. The value of magnetic resonance imaging of the lumbar spine to predict low-back pain in asymptomatic subjects: a seven-year follow-up study. *Journal of Bone & Joint Surgery - American Volume* 2001; **83**(9): 1306-11.
 91. Boden SD, McCowin P, Davis D, Dina T, Mark A, Wiesel S. Abnormal magnetic-resonance scans of the cervical spine in asymptomatic subjects. A prospective investigation. *Journal of Bone & Joint Surgery - American Volume* 1990; **72**(8): 1178-84.
 92. Gibson J, Waddell G. Surgical interventions for lumbar disc prolapse. *The Cochrane Library* 2007.
 93. Takeyama A, Naito M, Shiramizu K, Kiyama T. Prevalence of femoroacetabular impingement in Asian patients with osteoarthritis of the hip. *International orthopaedics* 2009; **33**(5): 1229-32.
 94. Hack K, Di Primio G, Rakhra K, Beaulé PE. Prevalence of cam-type femoroacetabular impingement morphology in asymptomatic volunteers. *Journal of Bone & Joint Surgery - American Volume* 2010; **92**(14): 2436-44.
 95. Siebenrock KA, Ferner F, Noble PC, Santore RF, Werlen S, Mamisch TC. The cam-type deformity of the proximal femur arises in childhood in response to vigorous sporting activity. *Clinical Orthopaedics & Related Research* 2011; **469**(11): 3229-40.

96. Johnson AC, Shaman MA, Ryan TG. Femoroacetabular impingement in former high-level youth soccer players. *American Journal of Sports Medicine* 2012; **40**(6): 1342-6.
97. Larson CM, Sikka RS, Sardelli MC, et al. Increasing alpha angle is predictive of athletic-related "hip" and "groin" pain in collegiate National Football League prospects. *Arthroscopy - Journal of Arthroscopic and Related Surgery* 2013; **29**(3): 405-10.
98. Gosvig KK, Jacobsen S, Sonne-Holm S, Gebuhr P. The prevalence of cam-type deformity of the hip joint: a survey of 4151 subjects of the Copenhagen Osteoarthritis Study. *Acta radiologica* 2008; **49**(4): 436-41.
99. Carey T, Key C, Oliver D, Biega T, Bojescul J. Prevalence of radiographic findings consistent with femoroacetabular impingement in military personnel with femoral neck stress fractures. *Journal of surgical orthopaedic advances* 2012; **22**(1): 54-8.
100. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine* 2009; **151**(4): 264-9.
101. Hoy D, Brooks P, Woolf A, et al. Assessing risk of bias in prevalence studies: modification of an existing tool and evidence of interrater agreement. *Journal of clinical epidemiology* 2012; **65**(9): 934-9.
102. Higgins J, Thompson SG. Quantifying heterogeneity in a meta - analysis. *Statistics in medicine* 2002; **21**(11): 1539-58.
103. Agricola R, Heijboer MP, Bierma-Zeinstra SM, Verhaar JA, Weinans H, Waarsing JH. Cam impingement causes osteoarthritis of the hip: a nationwide prospective cohort study (CHECK). *Annals of the rheumatic diseases* 2012; **72**(6): 918-23.
104. Jacobsen S, Sonne-Holm S, Søballe K, Gebuhr P, Lund B. Radiographic case definitions and prevalence of osteoarthrosis of the hip A survey of 4 151 subjects in the Osteoarthritis Substudy of the Copenhagen City Heart Study. *Acta orthopaedica* 2004; **75**(6): 713-20.
105. Laborie LB, Lehmann TG, Engesaeter IO, Eastwood DM, Engesaeter LB, Rosendahl K. Prevalence of radiographic findings thought to be associated with femoroacetabular impingement in a population-based cohort of 2081 healthy young adults. *Radiology* 2011; **260**(2): 494-502.
106. Leunig M, Jüni P, Werlen S, et al. Prevalence of cam and pincer-type deformities on hip MRI in an asymptomatic young Swiss female population: a cross-sectional study. *Osteoarthritis and Cartilage* 2013; **21**(4): 544-50.
107. Reichenbach S, Jüni P, Werlen S, et al. Prevalence of cam - type deformity on hip magnetic resonance imaging in young males: A cross - sectional study. *Arthritis care & research* 2010; **62**(9): 1319-27.
108. Hashimoto S, Fujishiro T, Hayashi S, Kanzaki N, Nishiyama T, Kurosaka M. Clinical importance of impingement deformities for hip osteoarthritis progression in a Japanese population. *International orthopaedics* 2014; **38**(8): 1609-14.
109. LaFrance R, Williams R, Madsen W, Maloney M, Drinkwater C, Giordano B. The Prevalence of Radiographic Criteria of Femoral Acetabular Impingement in Patients Undergoing Hip Arthroplasty Surgery. *Geriatric Orthopaedic Surgery and Rehabilitation* 2014; **5**(1): 21-6.

110. Bowler D, Flandry F. Prevalence of femoroacetabular impingement in younger patients undergoing total hip arthroplasty. *Journal of surgical orthopaedic advances* 2011; **21**(3): 122-5.
111. Goldin M, Anderson CN, Fredericson M, Safran MR, Stevens KJ. Femoral Neck Stress Fractures and Imaging Features of Femoroacetabular Impingement. *PM&R* 2015; **7**(6): 584-92.
112. Joo JH, Lee SC, Ahn HS, Park JS, Lee WJ, Jung KA. Evaluation of the alpha angle in asymptomatic adult hip joints: analysis of 994 hips. *Hip International* 2013; **23**(4): 395-9.
113. Jung KA, Restrepo C, Hellman M, AbdelSalam H, Morrison W, Parvizi J. The prevalence of cam-type femoroacetabular deformity in asymptomatic adults. *Journal of Bone & Joint Surgery - British Volume* 2011; **93**(10): 1303-7.
114. Mori R, Yasunaga Y, Yamasaki T, et al. Are cam and pincer deformities as common as dysplasia in Japanese patients with hip pain? *Bone & Joint Journal* 2014; **96**(2): 172-6.
115. Weir A, de Vos RJ, Moen M, Holmich P, Tol JL. Prevalence of radiological signs of femoroacetabular impingement in patients presenting with long-standing adductor-related groin pain. *British journal of sports medicine* 2011; **45**(1): 6-9.
116. Anderson LA, Kapron AL, Aoki SK, Peters CL. Coxa profunda: is the deep acetabulum overcovered? *Clinical orthopaedics and related research* 2012; **470**(12): 3375-82.
117. De Bruin F, Reijnierse M, Farhang-Razi V, Bloem JL. Radiographic signs associated with femoroacetabular impingement occur with high prevalence at all ages in a hospital population. *European Radiology* 2013; **23**(11): 3131-9.
118. Ida T, Nakamura Y, Hagio T, Naito M. Prevalence and characteristics of cam-type femoroacetabular deformity in 100 hips with symptomatic acetabular dysplasia: a case control study. *Journal of Orthopaedic Surgery* 2014; **9**: 93.
119. Fukushima K, Uchiyama K, Takahira N, et al. Prevalence of radiographic findings of femoroacetabular impingement in the Japanese population. *Journal of orthopaedic surgery and research* 2014; **9**(1): 25.
120. Dudda M, Kim Y-J, Zhang Y, et al. Morphologic differences between the hips of Chinese women and white women: Could they account for the ethnic difference in the prevalence of hip osteoarthritis? *Arthritis & Rheumatism* 2011; **63**(10): 2992-9.
121. Diesel CV, Ribeiro TA, Scheidt RB, De Souza Macedo CA, Galia CR. The prevalence of femoroacetabular impingement in radiographs of asymptomatic subjects: A cross-sectional study. *HIP International* 2015; **25**(3): 258-63.
122. Scheidt RB, Galia CR, Diesel CV, Rosito R, Macedo CA. Prevalence of radiographic markers of femoroacetabular impingement in asymptomatic adults. *Revista do Colegio Brasileiro de Cirurgioes* 2014; **41**(1): 36-42.
123. Tsitskaris K, Sharif K, Meacock LM, et al. The prevalence of cam-type femoroacetabular morphology in young adults and its effect on functional hip scores. *Hip International* 2012; **22**(1): 68-74.
124. Kang AC, Gooding AJ, Coates MH, Goh TD, Armour P, Rietveld J. Computed tomography assessment of hip joints in asymptomatic individuals in relation to femoroacetabular impingement. *American Journal of Sports Medicine* 2010; **38**(6): 1160-5.
125. Omoumi P, Thiery C, Michoux N, Malghem J, Lecouvet FE, Vande Berg BC. Anatomic features associated with femoroacetabular impingement are equally

- common in hips of old and young asymptomatic individuals without CT signs of osteoarthritis. *American Journal of Roentgenology* 2014; **202**(5): 1078-86.
126. Mimura T, Kawasaki T, Itakura S, et al. Prevalence of radiological femoroacetabular impingement in Japanese hip joints: detailed investigation with computed tomography. *Journal of Orthopaedic Science* 2015; **20**(4): 649-56.
127. Ergen FB, Vudali S, Sanverdi E, Dolgun A, Aydingoz U. CT assessment of asymptomatic hip joints for the background of femoroacetabular impingement morphology. *Diagnostic & Interventional Radiology* 2014; **20**(3): 271-6.
128. Van Houcke J, Yau WP, Yan CH, et al. Prevalence of radiographic parameters predisposing to femoroacetabular impingement in young asymptomatic Chinese and white subjects. *Journal of Bone & Joint Surgery - American Volume* 2015; **97**(4): 310-7.
129. Kim J, Choi JA, Lee E, Lee KR. Prevalence of Imaging Features on CT Thought to Be Associated With Femoroacetabular Impingement: A Retrospective Analysis of 473 Asymptomatic Adult Hip Joints. *American Journal of Roentgenology* 2015; **205**(1): W100-5.
130. Lahner M, Walter PA, von Schulze Pellengahr C, Hagen M, von Engelhardt LV, Lukas C. Comparative study of the femoroacetabular impingement (FAI) prevalence in male semiprofessional and amateur soccer players. *Archives of Orthopaedic & Trauma Surgery* 2014; **134**(8): 1135-41.
131. Gerhardt MB, Romero AA, Silvers HJ, Harris DJ, Watanabe D, Mandelbaum BR. The prevalence of radiographic hip abnormalities in elite soccer players. *American Journal of Sports Medicine* 2012; **40**(3): 584-8.
132. Tak I, Weir A, Langhout R, Waarsing JH, Stubbe J, Kerckhoffs G. The relationship between the frequency of football practice during skeletal growth and the presence of a cam deformity in adult elite football players. *British journal of sports medicine* 2015; **49**(9): 630-4.
133. Mariconda M, Cozzolino A, Di Pietto F, Ribas M, Bellotti V, Soldati A. Radiographic findings of femoroacetabular impingement in capoeira players. *Knee Surgery, Sports Traumatology, Arthroscopy* 2014; **22**(4): 874-81.
134. Lahner M, Bader S, Walter PA, et al. Prevalence of femoro-acetabular impingement in international competitive track and field athletes. *International orthopaedics* 2014; **38**(12): 2571-6.
135. Gosvig KK, Jacobsen S, Sonne-Holm S, Palm H, Troelsen A. Prevalence of malformations of the hip joint and their relationship to sex, groin pain, and risk of osteoarthritis: A population-based survey. *Journal of Bone & Joint Surgery - American Volume* 2010; **92**(5): 1162-9.
136. Erickson BJ, Cvetanovich GL, Frank RM, et al. International trends in arthroscopic hip preservation surgery—are we treating the same patient? *Journal of Hip Preservation Surgery* 2015; **2**(1): 28-41.
137. Tannast M, Fritsch S, Zheng G, Siebenrock KA, Steppacher SD. Which radiographic hip parameters do not have to be corrected for pelvic rotation and tilt? *Clinical orthopaedics and related research* 2015; **473**(4): 1255-66.
138. Rakhra KS, Sheikh AM, Allen D, Beaulé PE. Comparison of MRI alpha angle measurement planes in femoroacetabular impingement. *Clinical orthopaedics and related research* 2009; **467**(3): 660-5.
139. Siebenrock K, Wahab KA, Werlen S, Kalhor M, Leunig M, Ganz R. Abnormal extension of the femoral head epiphysis as a cause of cam impingement. *Clinical orthopaedics and related research* 2004; **418**: 54-60.

140. Dudda M, Albers C, Mamisch TC, Werlen S, Beck M. Do normal radiographs exclude asphericity of the femoral head-neck junction? *Clinical orthopaedics and related research* 2009; **467**(3): 651-9.
141. Khanna V, Caragianis A, DiPrimio G, Rakhra K, Beaulé PE. Incidence of Hip Pain in a Prospective Cohort of Asymptomatic Volunteers Is the Cam Deformity a Risk Factor for Hip Pain? *American Journal of Sports Medicine* 2014; **42**(4): 793-7.
142. Pollard TC, Villar RN, Norton MR, et al. Genetic influences in the aetiology of femoroacetabular impingement: A Sibling study. *Journal of Bone & Joint Surgery - British Volume* 2010; **92**(2): 209-16.
143. Philippon MJ, Ho CP, Briggs KK, Stull J, LaPrade RF. Prevalence of increased alpha angles as a measure of cam-type femoroacetabular impingement in youth ice hockey players. *American Journal of Sports Medicine* 2013; **41**(6): 1357-62.
144. Schmitz MR, Bittersohl B, Zaps D, Bomar JD, Pennock AT, Hosalkar HS. Spectrum of radiographic femoroacetabular impingement morphology in adolescents and young adults: an EOS-based double-cohort study. *Journal of Bone & Joint Surgery - American Volume* 2013; **95**(13): e90.
145. Monazzam S, Bomar JD, Dwek JR, Hosalkar HS, Pennock AT. Development and prevalence of femoroacetabular impingement-associated morphology in a paediatric and adolescent population: a CT study of 225 patients. *Bone & Joint Journal* 2013; **95-B**(5): 598-604.
146. Wells GS, B; O'Connell, D; Peterson, J; Welch, J; Losos, M; Tugwell, P;. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. 2013.
http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp.
147. Guyatt GH, Oxman AD, Vist GE, et al. Rating quality of evidence and strength of recommendations: GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ* 2008; **336**(7650): 924.
148. Dickenson E, Wall PD, Robinson B, et al. Prevalence of Cam Hip Shape Morphology: A Systematic Review. *Osteoarthritis and Cartilage* 2016; **24**(6): 949-61.
149. Kemp JL, Beasley I. 2016 international consensus on femoroacetabular impingement syndrome: the Warwick Agreement—why does it matter? *British journal of sports medicine* 2016; **50**(19): 1162-3.
150. Wall PD, Brown JS, Parsons N, Buchbinder R, Costa ML, Griffin D. Surgery for treating hip impingement (femoroacetabular impingement). *The Cochrane Library* 2014.
151. Murphy M, Black N, Lamping D, et al. Consensus development methods, and their use in clinical guideline development. *Health technology assessment (Winchester, England)* 1998; **2**(3): i.
152. Delbecq AL, Van de Ven AH. A group process model for problem identification and program planning. *The Journal of Applied Behavioral Science* 1971; **7**(4): 466-92.
153. Reiman MP, Thorborg K, Hölmich P. Femoroacetabular Impingement Surgery Is on the Rise—But What Is the Next Step? *Journal of Orthopaedic & Sports Physical Therapy* 2016; **46**(6): 406-8.
154. Freke M, Kemp J, Svege I, Risberg M, Semciw A, Crossley K. Physical impairments in symptomatic femoroacetabular impingement: a systematic review of the evidence. *British journal of sports medicine* 2016; **50**(19): 1180.

155. Agricola R, Weinans H. What is femoroacetabular impingement? *British journal of sports medicine* 2016; **50**(4): 196-7.
156. Reiman MP, Goode AP, Cook CE, Hölmich P, Thorborg K. Diagnostic accuracy of clinical tests for the diagnosis of hip femoroacetabular impingement/labral tear: a systematic review with meta-analysis. *British journal of sports medicine* 2014: bjsports-2014-094302.
157. Nepple JJ, Prather H, Trousdale RT, et al. Clinical diagnosis of femoroacetabular impingement. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**(suppl): S16-S9.
158. Sutter R, Dietrich TJ, Zingg PO, Pfirrmann CW. How useful is the alpha angle for discriminating between symptomatic patients with cam-type femoroacetabular impingement and asymptomatic volunteers? *Radiology* 2012; **264**(2): 514-21.
159. Fernandes L, Hagen KB, Bijlsma JW, et al. EULAR recommendations for the non-pharmacological core management of hip and knee osteoarthritis. *Annals of the rheumatic diseases* 2013; **72**(7): 1125-35.
160. Sankar WN, Nevitt M, Parvizi J, Felson DT, Leunig M. Femoroacetabular Impingement: Defining the Condition and its Role in the Pathophysiology of Osteoarthritis. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**(suppl): S7-S15.
161. Nüesch E, Dieppe P, Reichenbach S, Williams S, Iff S, Jüni P. All cause and disease specific mortality in patients with knee or hip osteoarthritis: population based cohort study. *BMJ* 2011; **342**: d1165.
162. Reiman MP, Thorborg K. Femoroacetabular impingement surgery: are we moving too fast and too far beyond the evidence? *British journal of sports medicine* 2015; **49**(12): 782-4.
163. Clohisy JC, Knaus ER, Hunt DM, Leshner JM, Harris-Hayes M, Prather H. Clinical presentation of patients with symptomatic anterior hip impingement. *Clinical orthopaedics and related research* 2009; **467**(3): 638-44.
164. Ayeni OR, Naudie D, Crouch S, et al. Surgical indications for treatment for femoroacetabular impingement with surgical hip dislocation. *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA* 2013; **21**(7): 1676-83.
165. Kivlan BR, Martin RL, Sekiya JK. Response to diagnostic injection in patients with femoroacetabular impingement, labral tears, chondral lesions, and extra-articular pathology. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2011; **27**(5): 619-27.
166. Bray ED, Sherafati M, Cutts CL, Stafford GH. The young adult hip: extra-articular causes of hip pain and how to pick the winners. *Journal of Hip preservation surgery* 2015; **2**(1): 51-5.
167. Khan W, Khan M, Alradwan H, Williams R, Simunovic N, Ayeni OR. Utility of Intra-articular Hip Injections for Femoroacetabular Impingement: A Systematic Review. *Orthopaedic Journal of Sports Medicine* 2015; **3**(9): 2325967115601030.
168. Shearer DW, Kramer J, Bozic KJ, Feeley BT. Is hip arthroscopy cost-effective for femoroacetabular impingement? *Clinical orthopaedics and related research* 2012; **470**(4): 1079-89.
169. Martin HD, Palmer IJ. History and physical examination of the hip: the basics. *Current reviews in musculoskeletal medicine* 2013; **6**(3): 219-25.
170. Martin RL, Kelly BT, Leunig M, et al. Reliability of clinical diagnosis in intraarticular hip diseases. *Knee Surgery, Sports Traumatology, Arthroscopy* 2010; **18**(5): 685-90.

171. Meyer DC, Beck M, Ellis T, Ganz R, Leunig M. Comparison of six radiographic projections to assess femoral head/neck asphericity. *Clinical orthopaedics and related research* 2006; **445**: 181-5.
172. Ross JR, Tannenbaum EP, Nepple JJ, Kelly BT, Larson CM, Bedi A. Functional acetabular orientation varies between supine and standing radiographs: implications for treatment of femoroacetabular impingement. *Clinical orthopaedics and related research* 2015; **473**(4): 1267-73.
173. Tannast M, Hanke MS, Zheng G, Steppacher SD, Siebenrock KA. What are the radiographic reference values for acetabular under- and overcoverage? *Clinical Orthopaedics & Related Research* 2015; **473**(4): 1234-46.
174. Kassarian A, Yoon LS, Belzile E, Connolly SA, Millis MB, Palmer WE. Triad of MR arthrographic findings in patients with cam-type femoroacetabular impingement. *Radiology* 2005; **236**(2): 588-92.
175. Smith TO, Simpson M, Ejindu V, Hing CB. The diagnostic test accuracy of magnetic resonance imaging, magnetic resonance arthrography and computer tomography in the detection of chondral lesions of the hip. *European Journal of Orthopaedic Surgery and Traumatology* 2013; **23**(3): 335-44.
176. Smith TO, Hilton G, Toms AP, Donell ST, Hing CB. The diagnostic accuracy of acetabular labral tears using magnetic resonance imaging and magnetic resonance arthrography: a meta-analysis. *European Radiology* 2011; **21**(4): 863-74.
177. Jamali AA, Mladenov K, Meyer DC, et al. Anteroposterior pelvic radiographs to assess acetabular retroversion: High validity of the “cross - over - sign” . *Journal of Orthopaedic Research* 2007; **25**(6): 758-65.
178. Villar R. Surgery for hip preservation—let the patient decide. *Journal of Hip Preservation Surgery* 2016; **3**(4): 243-4.
179. Clohisy JC, Baca G, Beaulé PE, et al. Descriptive epidemiology of femoroacetabular impingement: a North American cohort of patients undergoing surgery. *American Journal of Sports Medicine* 2013; **41**(6): 1348-56.
180. Clohisy JC, Kim Y-J. Femoroacetabular impingement research symposium. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**: vi-viii.
181. Clohisy JC, Kim Y-J, Lurie J, et al. Clinical trials in orthopaedics and the future direction of clinical investigations for femoroacetabular impingement. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**: S47-S52.
182. Nepple JJ, Byrd JT, Siebenrock KA, Prather H, Clohisy JC. Overview of treatment options, clinical results, and controversies in the management of femoroacetabular impingement. *Journal of the American Academy of Orthopaedic Surgeons* 2013; **21**(suppl): S53-S8.
183. Jordan K, Arden N, Doherty M, et al. EULAR Recommendations 2003: an evidence based approach to the management of knee osteoarthritis: Report of a Task Force of the Standing Committee for International Clinical Studies Including Therapeutic Trials (ESCISIT). *Annals of the rheumatic diseases* 2003; **62**(12): 1145-55.
184. Weir A, Brukner P, Delahunt E, et al. Doha agreement meeting on terminology and definitions in groin pain in athletes. *British journal of sports medicine* 2015; **49**(12): 768-74.
185. Bantel KA. Strategic clarity in banking: Role of top management-team demography. *Psychological Reports* 1993; **73**(3 suppl): 1187-201.
186. Murray AI. Top management group heterogeneity and firm performance. *Strategic Management Journal* 1989; **10**(S1): 125-41.

187. Jackson SE. Team composition in organizational settings: Issues in managing an increasingly diverse work force. Symposium on Group Productivity and Process, 1989, Texas A & MU, College Station, TX, US; 1991: Sage Publications, Inc; 1991.
188. Vinokur A, Burnstein E, Sechrest L, Wortman PM. Group decision making by experts: Field study of panels evaluating medical technologies. *Journal of Personality and Social Psychology* 1985; **49**(1): 70.
189. Rutjes AW, Reitsma JB, Vandenbroucke JP, Glas AS, Bossuyt PM. Case-control and two-gate designs in diagnostic accuracy studies. *Clinical chemistry* 2005; **51**(8): 1335-41.
190. Cohen JF, Korevaar DA, Altman DG, et al. STARD 2015 guidelines for reporting diagnostic accuracy studies: explanation and elaboration. *BMJ Open* 2016; **6**(11): e012799.
191. Rosset A, Spadola L, Ratib O. OsiriX: an open-source software for navigating in multidimensional DICOM images. *Journal of digital imaging* 2004; **17**(3): 205-16.
192. Tomczak RJ, Guenther K, Rieber A, Mergo P, Ros PR, Brambs HJ. MR imaging measurement of the femoral antetorsional angle as a new technique: comparison with CT in children and adults. *American Journal of Roentgenology* 1997; **168**(3): 791-4.
193. Youden WJ. Index for rating diagnostic tests. *Cancer* 1950; **3**(1): 32-5.
194. Obuchowski NA, McCLISH DK. Sample size determination for diagnostic accuracy studies involving binormal ROC curve indices. *Statistics in medicine* 1997; **16**(13): 1529-42.
195. Machin D, Campbell MJ, Tan S-B, Tan S-H. Sample size tables for clinical studies: John Wiley & Sons; 2011.
196. Siebenrock K-A, Peters CL, ABJS Carl T, Brighton workshop on hip preservation surgery: editorial comment. *Clinical Orthopaedics and Related Research*® 2012; **470**(12): 3281-3.
197. Cunningham D. Pelvis; 1922.
198. Lewinnek GE, Lewis J, Tarr R, Compere C, Zimmerman J. Dislocations after total hip-replacement arthroplasties. *Journal of Bone & Joint Surgery - American Volume* 1978; **60**(2): 217-20.
199. Dandachli W, Islam SU, Tippet R, Hall-Craggs MA, Witt JD. Analysis of acetabular version in the native hip: comparison between 2D axial CT and 3D CT measurements. *Skeletal radiology* 2011; **40**(7): 877-83.
200. Khan O, Witt J. Evaluation of the magnitude and location of Cam deformity using three dimensional CT analysis. *Bone & Joint Journal* 2014; **96**(9): 1167-71.
201. Dandachli W, Najefi A, Iranpour F, Lenihan J, Hart A, Cobb J. Quantifying the contribution of pincer deformity to femoro-acetabular impingement using 3D computerised tomography. *Skeletal radiology* 2012; **41**(10): 1295-300.
202. Dandachli W, Kannan V, Richards R, Shah Z, Hall-Craggs M, Witt J. Analysis of cover of the femoral head in normal and dysplastic hips: new CT-based technique. *Bone & Joint Journal* 2008; **90**(11): 1428-34.
203. Krekel P. Clinical Graphics 3D motion simulations. 2018. <https://www.clinicalgraphics.com/en/>.
204. Bouma HW, Hogervorst T, Audenaert E, Krekel P, van Kampen PM. Can Combining Femoral and Acetabular Morphology Parameters Improve the Characterization of Femoroacetabular Impingement? *Clinical orthopaedics and related research* 2015; **473**(4): 1396-403.

205. Usher-Smith JA, Sharp SJ, Griffin SJ. The spectrum effect in tests for risk prediction, screening, and diagnosis. *BMJ* 2016; **353**: i3139.
206. Coggon D, Barker D, Rose G. *Epidemiology for the Uninitiated*: John Wiley & Sons; 2009.
207. Standring S. *Gray's anatomy. The anatomical basis of clinical practice* 2008; **39**.
208. McCulloch P, Altman DG, Campbell WB, et al. No surgical innovation without evaluation: the IDEAL recommendations. *The Lancet* 2009; **374**(9695): 1105-12.
209. Knottnerus J, Muris J. Assessment of the accuracy of diagnostic tests: the cross-sectional study. *Journal of clinical epidemiology* 2003; **56**(11): 1118-28.
210. Zhang Q, Bhalerao A, Dickenson E, Hutchinson C. Active appearance pyramids for object parametrisation and fitting. *Medical image analysis* 2016; **32**: 101-14.
211. Network TAaR. TARN: University Hospital of Coventry and Warwickshire. 2017.
<https://www.tarn.ac.uk/Content.aspx?ca=15&c=2897&hid=8810&pcid=2912> (accessed 11/04/2017 2017).
212. Baker SP, o'Neill B, Haddon Jr W, Long WB. The injury severity score: a method for describing patients with multiple injuries and evaluating emergency care. *Journal of Trauma-Injury, Infection, and Critical Care* 1974; **14**(3): 187-96.
213. Statistics OfN. *Ethnicity and National Identity in England and Wales: 2011*: Office for National Statistics, 2012.
214. Statistics OfN. *2011 Census Aggregate data, 2011*.
215. Newcombe RG. Two - sided confidence intervals for the single proportion: comparison of seven methods. *Statistics in medicine* 1998; **17**(8): 857-72.
216. Lecky F, Woodford M, Bouamra O, Yates D. Lack of change in trauma care in England and Wales since 1994. *Emergency medicine journal* 2002; **19**(6): 520-3.
217. Krych AJ, Thompson M, Larson CM, Byrd JT, Kelly BT. Is posterior hip instability associated with cam and pincer deformity? *Clinical orthopaedics and related research* 2012; **470**(12): 3390-7.
218. Clegg TE, Roberts CS, Greene JW, Prather BA. Hip dislocations- Epidemiology, treatment, and outcomes. *Injury* 2010; **41**(4): 329-34.
219. Felson DT, Zhang Y. An update on the epidemiology of knee and hip osteoarthritis with a view to prevention. *Arthritis & Rheumatology* 1998; **41**(8): 1343-55.
220. Harrison M, Schajowicz F, Trueta J. Osteoarthritis of the hip: a study of the nature and evolution of the disease. *Bone & Joint Journal* 1953; **35**(4): 598-626.
221. Urwin M, Symmons D, Allison T, et al. Estimating the burden of musculoskeletal disorders in the community: the comparative prevalence of symptoms at different anatomical sites, and the relation to social deprivation. *Annals of the rheumatic diseases* 1998; **57**(11): 649-55.
222. Birrell F, Lunt M, Macfarlane G, Silman A. Defining hip pain for population studies. *Annals of the rheumatic diseases* 2005; **64**(1): 95-8.
223. Thiem U, Lamsfuß R, Günther S, et al. Prevalence of self-reported pain, joint complaints and knee or hip complaints in adults aged ≥ 40 years: a cross-sectional survey in Herne, Germany. *PloS one* 2013; **8**(4): e60753.
224. Frankel S, Eachus J, Pearson N, et al. Population requirement for primary hip-replacement surgery: a cross-sectional study. *The Lancet* 1999; **353**(9161): 1304-9.

225. Farrally M, Cochran A, Crews D, et al. Golf science research at the beginning of the twenty-first century. *Journal of sports sciences* 2003; **21**(9): 753-65.
226. Committee IO. International Golf Federation. 2015. <http://www.olympic.org/igf>.
227. Gulgin H, Armstrong C, Gribble P. Hip rotational velocities during the full golf swing. *Journal of sports science & medicine* 2009; **8**(2): 296.
228. Audenaert EA, Peeters I, Vigneron L, Baelde N, Pattyn C. Hip morphological characteristics and range of internal rotation in femoroacetabular impingement. *American Journal of Sports Medicine* 2012; **40**(6): 1329-36.
229. Crockett HC, Gross LB, Wilk KE, et al. Osseous adaptation and range of motion at the glenohumeral joint in professional baseball pitchers. *American Journal of Sports Medicine* 2002; **30**(1): 20-6.
230. Osbahr DC, Cannon DL, Speer KP. Retroversion of the humerus in the throwing shoulder of college baseball pitchers. *American Journal of Sports Medicine* 2002; **30**(3): 347-53.
231. Yamamoto N, Itoi E, Minagawa H, et al. Why is the humeral retroversion of throwing athletes greater in dominant shoulders than in nondominant shoulders? *Journal of shoulder and elbow surgery* 2006; **15**(5): 571-5.
232. Mohtadi NG, Griffin DR, Pedersen ME, et al. The development and validation of a self-administered quality-of-life outcome measure for young, active patients with symptomatic hip disease: the International Hip Outcome Tool (iHOT-33). *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2012; **28**(5): 595-610. e1.
233. Griffin DR, Parsons N, Mohtadi NG, Safran MR. A short version of the International Hip Outcome Tool (iHOT-12) for use in routine clinical practice. *Arthroscopy: The Journal of Arthroscopic & Related Surgery* 2012; **28**(5): 611-8.
234. Prather H, Harris-Hayes M, Hunt DM, Steger-May K, Mathew V, Clohisy JC. Reliability and agreement of hip range of motion and provocative physical examination tests in asymptomatic volunteers. *PM&R* 2010; **2**(10): 888-95.
235. Reichenbach S, Jüni P, Nüesch E, Frey F, Ganz R, Leunig M. An examination chair to measure internal rotation of the hip in routine settings: a validation study. *Osteoarthritis and Cartilage* 2010; **18**(3): 365-71.
236. Holm S. A simple sequentially rejective multiple test procedure. *Scandinavian journal of statistics* 1979; **6**(2): 65-70.
237. Cabri J, Sousa JP, Kots M, Barreiros J. Golf-related injuries: A systematic review. *European Journal of Sport Science* 2009; **9**(6): 353-66.
238. Abrams GD, Renstrom PA, Safran MR. Epidemiology of musculoskeletal injury in the tennis player. *British journal of sports medicine* 2012; **46**(7): 492-8.
239. Gosheger G, Liem D, Ludwig K, Greshake O, Winkelmann W. Injuries and overuse syndromes in golf. *American Journal of Sports Medicine* 2003; **31**(3): 438-43.
240. Dickenson E, O'Connor P, Robinson P, et al. Hip morphology in elite golfers: asymmetry between lead and trail hips. *British Journal of Sports Medicine* 2016; **50**(17): 1081-6.
241. Burnett RSJ, Della Rocca G, Prather H, Curry M, Maloney WJ, Clohisy JC. Clinical presentation of patients with tears of the acetabular labrum. *JBJS* 2006; **88**(7): 1448-57.
242. Fabry G, Macewen GD, Shands Jr A. Torsion of the femur. *Journal of Bone & Joint Surgery - American Volume* 1973; **55**(8): 1726-38.

243. Larson CM, Safran MR, Brcka D, Vaughn Z, Giveans MR. Prevalence of radiographic hip pathomorphology in patients presenting to an orthopaedic Clinic with "Hip" Pain. *Arthroscopy - Journal of Arthroscopic and Related Surgery* 2012; **2**: e47.
244. Ganz R, Leunig M, Leunig-Ganz K, Harris WH. The etiology of osteoarthritis of the hip. *Clinical orthopaedics and related research* 2008; **466**(2): 264-72.
245. Bradford-Hill A. The environment and disease: association or causation? *Proceedings of the Royal Society of Medicine* 1965; **58**(5): 295.
246. Britton A, McKee M, Black N, McPherson K, Sanderson C, Bain C. Choosing between randomised and non-randomised studies: a systematic review. *Health technology assessment (Winchester, England)* 1997; **2**(13): i-iv, 1-124.
247. Ross S, Grant A, Counsell C, Gillespie W, Russell I, Prescott R. Barriers to participation in randomised controlled trials: a systematic review. *Journal of clinical epidemiology* 1999; **52**(12): 1143-56.
248. Ergina PL, Cook JA, Blazeby JM, et al. Challenges in evaluating surgical innovation. *The Lancet* 2009; **374**(9695): 1097-104.
249. Agricola R, Heijboer MP, Roze RH, et al. Pincer deformity does not lead to osteoarthritis of the hip whereas acetabular dysplasia does: acetabular coverage and development of osteoarthritis in a nationwide prospective cohort study (CHECK). *Osteoarthritis and Cartilage* 2013; **21**(10): 1514-21.
250. Pollard TC, Batra RN, Judge A, et al. The hereditary predisposition to hip osteoarthritis and its association with abnormal joint morphology. *Osteoarthritis and Cartilage* 2013; **21**(2): 314-21.
251. Thomas GE, Palmer AJ, Batra RN, et al. Subclinical deformities of the hip are significant predictors of radiographic osteoarthritis and joint replacement in women. A 20 year longitudinal cohort study. *Osteoarthritis and Cartilage* 2014; **22**(10): 1504-10.
252. Nicholls AS, Kiran A, Pollard TC, et al. The association between hip morphology parameters and nineteen - year risk of end - stage osteoarthritis of the hip: A nested case-control study. *Arthritis & Rheumatism* 2011; **63**(11): 3392-400.
253. Nelson AE, Stiller JL, Shi XA, et al. Measures of hip morphology are related to development of worsening radiographic hip osteoarthritis over 6 to 13 year follow-up: The Johnston County Osteoarthritis Project. *Osteoarthritis and Cartilage* 2016; **24**(3): 443-50.
254. Goodman DA, Feighan JE, Smith AD, Latimer B, Buly RL, Cooperman DR. Subclinical slipped capital femoral epiphysis. Relationship to osteoarthrosis of the hip.[Erratum appears in J Bone Joint Surg Am 1999 Apr;81(4):592]. *Journal of Bone & Joint Surgery - American Volume* 1997; **79**(10): 1489-97.
255. Doherty M, Courtney P, Doherty S, et al. Nonspherical femoral head shape (pistol grip deformity), neck shaft angle, and risk of hip osteoarthritis: a case-control study. *Arthritis & Rheumatism* 2008; **58**(10): 3172-82.
256. Barros HJ, Camanho GL, Bernabe AC, Rodrigues MB, Leme LE. Femoral head-neck junction deformity is related to osteoarthritis of the hip. *Clinical Orthopaedics & Related Research* 2010; **468**(7): 1920-5.
257. Mamisch TC, Kain MSH, Bittersohl B, et al. Delayed gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC) in Femoacetabular impingement. *Journal of Orthopaedic Research* 2011; **29**(9): 1305-11.

258. Hartofilakidis G, Bardakos NV, Babis GC, Georgiades G. An examination of the association between different morphotypes of femoroacetabular impingement in asymptomatic subjects and the development of osteoarthritis of the hip. *Journal of Bone & Joint Surgery - British Volume* 2011; **93**(5): 580-6.
259. Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ. The John Charnley Award: Redefining the Natural History of Osteoarthritis in Patients With Hip Dysplasia and Impingement. *Clinical orthopaedics and related research* 2017; **475**(2): 336-50.
260. Bardakos N, Villar R. Predictors of progression of osteoarthritis in femoroacetabular impingement a radiological study with a minimum of ten years follow-up. *Journal of Bone & Joint Surgery - British Volume* 2009; **91**(2): 162-9.
261. Gosvig KK, Jacobsen S, Sonne-Holm S, Palm H, Troelsen A. Prevalence of malformations of the hip joint and their relationship to sex, groin pain, and risk of osteoarthritis: A population-based survey. *Journal of Bone and Joint Surgery - Series A* 2010; **92**(5): 1162-9.
262. Nardo L, Parimi N, Liu F, et al. Femoroacetabular Impingement: Prevalent and Often Asymptomatic in Older Men: The Osteoporotic Fractures in Men Study. *Clinical Orthopaedics & Related Research* 2015; **473**(8): 2578-86.
263. Pollard TCB, McNally EG, Wilson DC, et al. Localized cartilage assessment with three-dimensional dGEMRIC in asymptomatic hips with normal morphology and cam deformity. *Journal of Bone & Joint Surgery - American Volume* 2010; **92**(15): 2557-69.
264. Reichenbach S, Leunig M, Werlen S, et al. Association between cam-type deformities and magnetic resonance imaging-detected structural hip damage: a cross-sectional study in young men. *Arthritis & Rheumatism* 2011; **63**(12): 4023-30.
265. Beaulé PE, Hynes K, Parker G, Kemp KA. Can the alpha angle assessment of cam impingement predict acetabular cartilage delamination? *Clinical Orthopaedics & Related Research* 2012; **470**(12): 3361-7.
266. Johnston TL, Schenker ML, Briggs KK, Philippon MJ. Relationship between offset angle alpha and hip chondral injury in femoroacetabular impingement. *Arthroscopy - Journal of Arthroscopic and Related Surgery* 2008; **24**(6): 669-75.
267. Oner A, Koksak A, Sofu H, Aykut US, Yildirim T, Kaygusuz MA. The prevalence of femoroacetabular impingement as an aetiologic factor for end-stage degenerative osteoarthritis of the hip joint: analysis of 1,000 cases. *Hip International* 2016; **26**(2): 164-8.
268. Tanzer M, Noiseux N. Osseous abnormalities and early osteoarthritis: the role of hip impingement. *Clinical Orthopaedics & Related Research* 2004; **429**: 170-7.
269. Kim WY, Hutchinson CE, Andrew JG, Allen PD. The relationship between acetabular retroversion and osteoarthritis of the hip. *Journal of Bone & Joint Surgery - British Volume* 2006; **88**(6): 727-9.
270. Weinberg DS, Williamson DFK, Millis MB, Liu RW. Decreased and increased relative acetabular volume predict the development of osteoarthritis of the hip. *Bone and Joint Journal* 2017; **99B**(4): 432-9.
271. Smith R, Egger P, Coggon D, Cawley M, Cooper C. Osteoarthritis of the hip joint and acetabular dysplasia in women. *Annals of the rheumatic diseases* 1995; **54**(3): 179-81.

272. Lane NE, Lin P, Christiansen L, et al. Association of mild acetabular dysplasia with an increased risk of incident hip osteoarthritis in elderly white women: the study of osteoporotic fractures. *Arthritis & Rheumatology* 2000; **43**(2): 400-4.
273. Cooper C, Inskip H, Croft P, et al. Individual risk factors for hip osteoarthritis: obesity, hip injury and physical activity. *American journal of epidemiology* 1998; **147**(6): 516-22.
274. Solomon L. Patterns of osteoarthritis of the hip. *Journal of Bone & Joint Surgery - British Volume* 1976; **58**(2): 176-83.
275. Stulberg SD, Cooperman DR, Wallensten R. The natural history of Legg-Calvé-Perthes disease. *Journal of Bone & Joint Surgery - American Volume* 1981; **63**(7): 1095-108.
276. Yrjönen T. Long-term prognosis of Legg-Calve-Perthes disease: a meta-analysis. *Journal of Pediatric Orthopaedics* 1999; **8**(3): 169-72.
277. Jacobsen S, Sonne-Holm S. Hip dysplasia: a significant risk factor for the development of hip osteoarthritis. A cross-sectional survey. *Rheumatology* 2004; **44**(2): 211-8.
278. Jessel RH, Zurakowski D, Zilkens C, Burstein D, Gray ML, Kim Y-J. Radiographic and patient factors associated with pre-radiographic osteoarthritis in hip dysplasia. *Journal of Bone & Joint Surgery - American Volume* 2009; **91**(5): 1120-9.
279. Howick J, Glasziou P, Aronson JK. The evolution of evidence hierarchies: what can Bradford Hill's 'guidelines for causation' contribute? *Journal of the Royal Society of Medicine* 2009; **102**(5): 186-94.
280. Mapstone J, Elbourne D, Roberts IG. Strategies to improve recruitment to research studies. *The Cochrane Library* 2007.
281. Treweek S, Mitchell E, Pitkethly M, et al. Strategies to improve recruitment to randomised controlled trials. *Cochrane Database Systematic Reviews* 2010; **4**(4).
282. Pritzker K, Gay S, Jimenez S, et al. Osteoarthritis cartilage histopathology: grading and staging. *Osteoarthritis and cartilage* 2006; **14**(1): 13-29.
283. Buckwalter JA, Mankin HJ, Grodzinsky AJ. Articular cartilage and osteoarthritis. *Instructional Course Lectures-American Academy of Orthopaedic Surgeons* 2005; **54**: 465.
284. Hingsammer AM, Kalish LA, Stelzeneder D, et al. Does periacetabular osteotomy for hip dysplasia modulate cartilage biochemistry? *Journal of Bone & Joint Surgery - American Volume* 2015; **97**(7): 544-50.
285. Hingsammer AM, Miller PE, Millis MB, Kim Y-J. Does periacetabular osteotomy have depth-related effects on the articular cartilage of the hip? *Clinical orthopaedics and related research* 2015; **473**(12): 3735-43.
286. Borthakur A, Shapiro E, Beers J, Kudchodkar S, Kneeland J, Reddy R. Sensitivity of MRI to proteoglycan depletion in cartilage: comparison of sodium and proton MRI. *Osteoarthritis and Cartilage* 2000; **8**(4): 288-93.
287. Madelin G, Babb JS, Xia D, Chang G, Jerschow A, Regatte RR. Reproducibility and repeatability of quantitative sodium magnetic resonance imaging in vivo in articular cartilage at 3 T and 7 T. *Magnetic resonance in medicine* 2012; **68**(3): 841-9.
288. Wang L, Wu Y, Chang G, et al. Rapid isotropic 3D - sodium MRI of the knee joint in vivo at 7T. *Journal of Magnetic Resonance Imaging* 2009; **30**(3): 606-14.

289. Duvvuri U, Kudchodkar S, Reddy R, Leigh J. T1 ρ relaxation can assess longitudinal proteoglycan loss from articular cartilage in vitro. *Osteoarthritis and cartilage* 2002; **10**(11): 838-44.
290. Nishioka H, Hirose J, Nakamura E, et al. T1 ρ and T2 mapping reveal the in vivo extracellular matrix of articular cartilage. *Journal of Magnetic Resonance Imaging* 2012; **35**(1): 147-55.
291. Matzat SJ, van Tiel J, Gold GE, Oei EH. Quantitative MRI techniques of cartilage composition. *Quantitative imaging in medicine and surgery* 2013; **3**(3): 162.
292. Rakhra K, Lattanzio P, Cardenas-Blanco A, Cameron I, Beaulé P. Can T1-rho MRI detect acetabular cartilage degeneration in femoroacetabular impingement? *Journal of Bone & Joint Surgery - British Volume* 2012; **94**(9): 1187-92.
293. Beulé PE, Speirs AD, Anwender H, et al. Surgical Correction of Cam Deformity in Association with Femoroacetabular Impingement and Its Impact on the Degenerative Process within the Hip Joint. *Journal of Bone & Joint Surgery - American Volume* 2017; **99**(16): 1373-81.
294. Bashir A, Gray M, Hartke J, Burstein D. Nondestructive imaging of human cartilage glycosaminoglycan concentration by MRI. *Magnetic resonance in medicine* 1999; **41**(5): 857-65.
295. Cunningham T, Jessel R, Zurakowski D, Millis MB, Kim YJ. Delayed gadolinium-enhanced magnetic resonance imaging of cartilage to predict early failure of Bernese periacetabular osteotomy for hip dysplasia. *Journal of Bone & Joint Surgery - American Volume* 2006; **88**(7): 1540-8.
296. Murphy NJ, Eyles J, Bennell KL, et al. Protocol for a multi-centre randomised controlled trial comparing arthroscopic hip surgery to physiotherapy-led care for femoroacetabular impingement (FAI): the Australian FASHIoN trial. *BMC musculoskeletal disorders* 2017; **18**(1): 406.
297. Palmer A, Ayyar-Gupta V, Dutton S, et al. Protocol for the Femoroacetabular Impingement Trial (FAIT). *Bone and Joint Research* 2014; **3**(11): 321-7.
298. Grobner T. Gadolinium—a specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? *Nephrology Dialysis Transplantation* 2006; **21**(4): 1104-8.
299. Tiderius CJ, Jessel R, Kim YJ, Burstein D. Hip dGEMRIC in asymptomatic volunteers and patients with early osteoarthritis: the influence of timing after contrast injection. *Magnetic resonance in medicine* 2007; **57**(4): 803-5.
300. Tiderius C, Hori M, Williams A, et al. dGEMRIC as a function of BMI. *Osteoarthritis and cartilage* 2006; **14**(11): 1091-7.
301. Hesper T, Hosalkar HS, Bittersohl D, et al. T2* mapping for articular cartilage assessment: principles, current applications, and future prospects. *Skeletal radiology* 2014; **43**(10): 1429-45.
302. Watanabe A, Boesch C, Siebenrock K, Obata T, Anderson SE. T2 mapping of hip articular cartilage in healthy volunteers at 3T: a study of topographic variation. *Journal of Magnetic Resonance Imaging* 2007; **26**(1): 165-71.
303. Nishii T, Shiomi T, Tanaka H, Yamazaki Y, Murase K, Sugano N. Loaded cartilage T2 mapping in patients with hip dysplasia. *Radiology* 2010; **256**(3): 955-65.
304. Hamada H, Nishii T, Tamura S, et al. Three dimensional distribution of hip cartilage T2 mapping assessed by radial mr imaging: Comparison between healthy

- volunteers and patients with hip dysplasia. *Osteoarthritis and Cartilage* 2014; **22**: S353-S4.
305. Chavhan GB, Babyn PS, Thomas B, Shroff MM, Haacke EM. Principles, techniques, and applications of T2*-based MR imaging and its special applications. *Radiographics* 2009; **29**(5): 1433-49.
306. Ellermann J, Ziegler C, Nissi MJ, et al. Acetabular Cartilage Assessment in Patients with Femoroacetabular Impingement by Using T2* Mapping with Arthroscopic Verification. *Radiology* 2014; **271**(2): 512-23.
307. Bittersohl B, Miese F, Hosalkar H, et al. T2* mapping of hip joint cartilage in various histological grades of degeneration. *Osteoarthritis and Cartilage* 2012; **20**(7): 653-60.
308. Hesper T, Hosalkar HS, Schleich C, et al. T2* Mapping for Hip Joint Cartilage Assessment Pre-MRI Exercise and Time of Imaging Do Not Bias the T2* Measurement in Asymptomatic Volunteers. *Cartilage* 2016; **8**(4): 400-5.
309. Bittersohl B, Miese FR, Hosalkar HS, et al. T2 mapping of hip joint cartilage in various histological grades of degeneration. *Osteoarthritis and Cartilage* 2012; **20**(7): 653-60.
310. Craig P, Dieppe P, Macintyre S, Michie S, Nazareth I, Petticrew M. Developing and evaluating complex interventions: the new Medical Research Council guidance. *BMJ* 2008; **337**: a1655.
311. Beall DP, Sweet CF, Martin HD, et al. Imaging findings of femoroacetabular impingement syndrome. *Skeletal radiology* 2005; **34**(11): 691-701.
312. Ellermann J, Goerke U, Morgan P, et al. Simultaneous bilateral hip joint imaging at 7 Tesla using fast transmit B1 shimming methods and multichannel transmission - a feasibility study. *NMR in Biomedicine* 2012; **25**(10): 1202-8.
313. Roemer F, Hunter D, Winterstein A, et al. Hip Osteoarthritis MRI Scoring System (HOAMS): reliability and associations with radiographic and clinical findings. *Osteoarthritis and Cartilage* 2011; **19**(8): 946-62.
314. Blumenkrantz G, Majumdar S. Quantitative magnetic resonance imaging of articular cartilage in osteoarthritis. *European Cells and Materials* 2007; **13**(7): 75-86.
315. Naish JH, Xanthopoulos E, Hutchinson CE, Waterton JC, Taylor CJ. MR measurement of articular cartilage thickness distribution in the hip. *Osteoarthritis and Cartilage* 2006; **14**(10): 967-73.
316. Eckstein F, Guermazi A, Gold G, et al. Imaging of cartilage and bone: promises and pitfalls in clinical trials of osteoarthritis. *Osteoarthritis and Cartilage* 2014; **22**(10): 1516-32.
317. Eckstein F, Nevitt M, Gimona A, et al. Rates of change and sensitivity to change in cartilage morphology in healthy knees and in knees with mild, moderate, and end - stage radiographic osteoarthritis: Results from 831 participants from the osteoarthritis initiative. *Arthritis care & research* 2011; **63**(3): 311-9.
318. Realpe A, Adams A, Wall P, Griffin D, Donovan JL. A new simple six-step model to promote recruitment to RCTs was developed and successfully implemented. *Journal of clinical epidemiology* 2016; **76**: 166-74.
319. Griffin DR, Dickenson E, Wall PD, et al. The feasibility of conducting a randomised controlled trial comparing arthroscopic hip surgery to conservative care for patients with femoroacetabular impingement syndrome: the FASHIoN feasibility study. *Journal of Hip Preservation Surgery* 2016; **3**(4): 304-11.

320. Schmaranzer F, Haefeli PC, Hanke MS, et al. How does the dGEMRIC index change after surgical treatment for FAI? A prospective controlled study: preliminary results. *Clinical orthopaedics and related research* 2017; **475**(4): 1080-99.
321. Schwartz D, Lellouch J. Explanatory and pragmatic attitudes in therapeutical trials. *Journal of chronic diseases* 1967; **20**(8): 637-48.
322. Maintz JA, Viergever MA. A survey of medical image registration. *Medical image analysis* 1998; **2**(1): 1-36.
323. Bittersohl B, Miese FR, Hosalkar HS, et al. T2* mapping of acetabular and femoral hip joint cartilage at 3 T: A prospective controlled study. *Investigative Radiology* 2012; **47**(7): 392-7.
324. Apprich S, Mamisch T, Welsch G, et al. Evaluation of articular cartilage in patients with femoroacetabular impingement (FAI) using T2* mapping at different time points at 3.0 Tesla MRI: a feasibility study. *Skeletal radiology* 2012; **41**(8): 987-95.
325. Balamoody S, Williams TG, Wolstenholme C, et al. Magnetic resonance transverse relaxation time T2 of knee cartilage in osteoarthritis at 3-T: a cross-sectional multicentre, multivendor reproducibility study. *Skeletal radiology* 2013; **42**(4): 511-20.
326. Buxton M. Problems in the economic appraisal of new health technology: the evaluation of heart transplants in the UK. *Economic appraisal of health technology in the European Community* 1987: 103-18.
327. Griffin DR, Dickenson EJ, Wall PDH, et al. Hip arthroscopy versus best conservative care for the treatment of femoroacetabular impingement syndrome (UK FASHIoN): a multicentre randomised controlled trial. *The Lancet* 2018; **391**(10136): 2225-35.
328. Wolf S. The pharmacology of placebos. *Pharmacological reviews* 1959; **11**(4): 689-704.
329. Johnson AG. Surgery as a placebo. *The Lancet* 1994; **344**(8930): 1140-2.
330. Beard DJ, Rees JL, Cook JA, et al. Arthroscopic subacromial decompression for subacromial shoulder pain (CSAW): a multicentre, pragmatic, parallel group, placebo-controlled, three-group, randomised surgical trial. *The Lancet* 2017; **391**(10118): 329-38.
331. Hotopf M. The pragmatic randomised controlled trial. *Advances in Psychiatric Treatment* 2002; **8**(5): 326-33.
332. Thorpe KE, Zwarenstein M, Oxman AD, et al. A pragmatic-explanatory continuum indicator summary (PRECIS): a tool to help trial designers. *Journal of clinical epidemiology* 2009; **62**(5): 464-75.
333. Loudon K, Treweek S, Sullivan F, Donnan P, Thorpe KE, Zwarenstein M. The PRECIS-2 tool: designing trials that are fit for purpose. *BMJ* 2015; **350**: h2147.
334. Agricola R, Waarsing JH, Arden NK, et al. Cam impingement of the hip-a risk factor for hip osteoarthritis. *Nature Reviews Rheumatology* 2013; **9**(10): 630-4.
335. Palmer A, Fernquest S, Gimpel M, et al. Physical activity during adolescence and the development of cam morphology: a cross-sectional cohort study of 210 individuals. *British journal of sports medicine* 2017: bjsports-2017-097626.
336. Masjedi M, Nightingale C, Azimi D, Cobb J. The three-dimensional relationship between acetabular rim morphology and the severity of femoral cam lesions. *Bone & Joint Journal* 2013; **95**(3): 314-9.

337. Cobb J, Logishetty K, Davda K, Iranpour F. Cams and pincer impingement are distinct, not mixed: the acetabular pathomorphology of femoroacetabular impingement. *Clinical orthopaedics and related research* 2010; **468**(8): 2143-51.
338. Diamond L, Bennell K, Wrigley T, Hinman R, O'Donnell J, Hodges P. Squatting biomechanics in individuals with symptomatic femoroacetabular impingement: Unconstrained and constrained tasks. *Osteoarthritis and Cartilage* 2016; **24**: S100-S1.
339. Eachus J, Williams M, Chan P, et al. Deprivation and cause specific morbidity: evidence from the Somerset and Avon survey of health. *BMJ* 1996; **312**(7026): 287-92.
340. Mast NH, Impellizzeri F, Keller S, Leunig M. Reliability and agreement of measures used in radiographic evaluation of the adult hip. *Clinical orthopaedics and related research* 2011; **469**(1): 188-99.
341. Peelle MW, Della Rocca GJ, Maloney WJ, Curry MC, Clohisy JC. Acetabular and femoral radiographic abnormalities associated with labral tears. *Clinical orthopaedics and related research* 2005; **441**: 327-33.
342. Dudda M, Kim YJ, Zhang Y, et al. Morphologic differences between the hips of Chinese women and white women: could they account for the ethnic difference in the prevalence of hip osteoarthritis? *Arthritis & Rheumatism* 2011; **63**(10): 2992-9.
343. Tönnis D, Heinecke A. Current concepts review-acetabular and femoral anteversion: relationship with osteoarthritis of the hip. *JBJS* 1999; **81**(12): 1747-70.
344. Chosa E, Tajima N. Anterior acetabular head index of the hip on false-profile views. *Bone & Joint Journal* 2003; **85**(6): 826-9.

11 Appendix

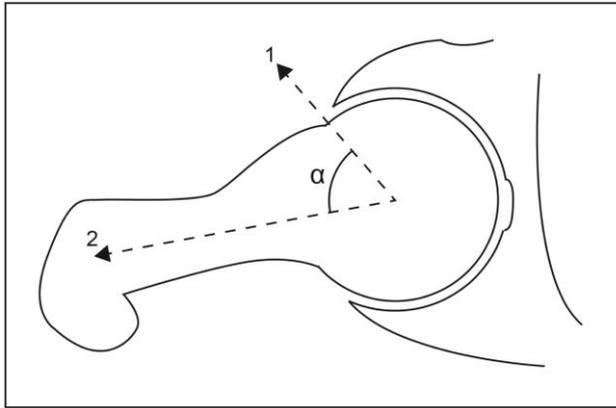
11.1 Chapter 1; additional material

11.1.1 Measures of Proximal Femoral Morphology

Alpha (α) angles

α angles are widely used, easily reproducible and have been shown to be a valid, agreeable and reliable method for detecting cam morphology.^{62,340} Mast et al showed that measurements of α angles had an intra class correlation coefficient of 0.83 and standard error of measurement of 6°. A diagrammatic representation of how to measure an α angle is shown in Figure 55. Line 1 is drawn between the center of the femoral head and the anterior point where the bony contour exceeds the radius of the head. Line 2 is drawn along the axis of the femoral neck, between the narrowest point of the neck and the center of the femoral head. The alpha angle is measured between line 1 and 2. When first described α angles were measured on axial oblique MRI, in the plane of the femoral neck, at the anterior (3 o'clock) position.⁶² Notzli used a cut of value of 50.5° to determine the presence of a cam deformity.⁶² α angles have since been adapted and are now measured at different positions around the femoral neck and by different imaging modalities. Numerous values of α angle have been used to define cam lesions from 50° to 83°.^{45,98}

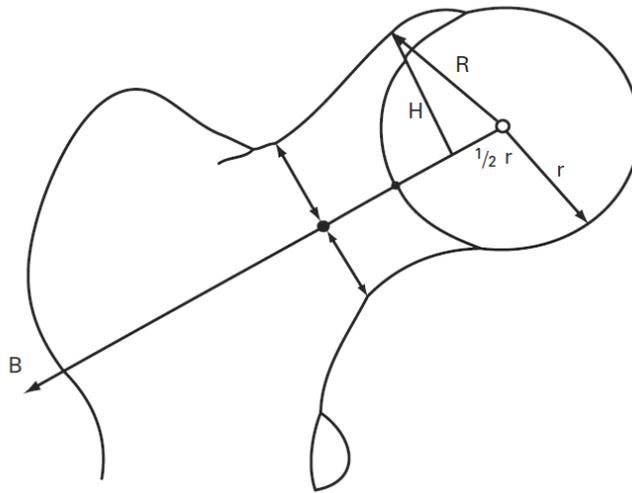
Figure 55 Diagrammatic representation of how to measure an alpha angle (source Notzli et al 2002⁶²)



Triangular Index

Triangular index was described by Gosvig et al in 2007, a diagrammatic representation is shown in Figure 56.⁶³ The triangular index is measured by drawing a line, B, along the axis of the femoral neck between the centre of the femoral head and the middle of the narrowest aspect of the neck. The radius, r , of the head is calculated. Line H is measured perpendicular to line B, from a point $\frac{1}{2} r$ proximal to the center of the femoral head along line B. Line H extends to the edge of the bony cortex. Using pythagorus theorem line R (see Figure 56) is calculated. If $R > (r+2\text{mm})$ a cam deformity determined to be present. The interclass coefficient for triangular index was measured to be 0.95 and the intraclass coefficient between 0.97 and 0.98.⁶³

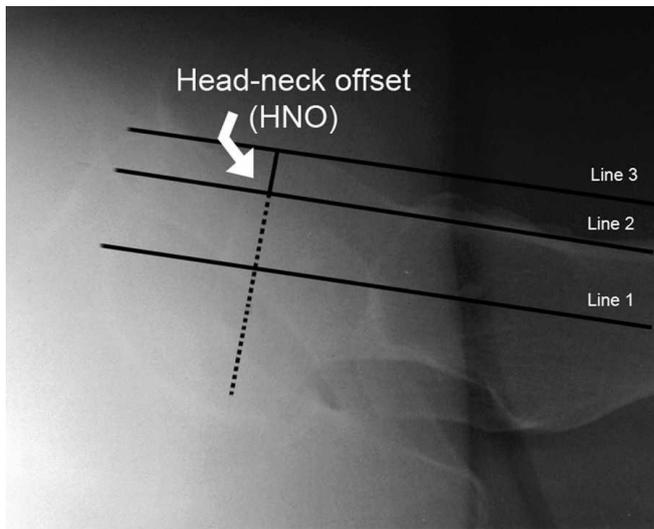
Figure 56 Diagrammatic representation of Triangular Index (source: Gosvig et al 2007⁶³)



Head neck offset and head neck offset ratios

Head neck offset ratios was first described by Eijer et al in 2001 as a method of determining proximal femoral morphology on cross table radiographs.¹² Figure 57 shows how head neck offset is determined. The first line is drawn along the axis of the femoral neck (although not necessarily through the center of the head), a second and third parallel lines are drawn which mark the anterior border of femoral neck and head respectively. The distance between the second and third lines determines the head neck offset. The head neck offset ratio is defined as the head neck offset distance in relation to the diameter of the femoral head. It has been proposed that an offset distance of <8mm and a head neck offset ratio of less than 0.17 demonstrate cam deformity.⁵⁸

Figure 57 Cross table lateral xray of right hip demonstrating how head neck offset is determined
(source Peelle 2005 ³⁴¹)



Head neck offset grade

Further subjective assessments of the head neck junction have been made.

Reichenbach et al 2010 described a semi quantitative method to assess the head neck junction using radial of the femoral neck on MRI.¹⁰⁷ Using this method grade 0 is normal with no evidence of a aspherical femoral shape on any of the sequences; grade 1 possible deformity with cortical irregularity and a possible decrease of the anterior head-neck offset; grade 2 definite deformity with an established decrease of the anterior head-neck offset; and 3 severe deformity with a large decrease of the anterior head-neck offset.¹⁰⁷ Using this method Reichenbach determined that grades 2 and 3 represented cam morphology.

Presence of Pistol Grip deformity

Other subjective assessments include determining the presence of a “pistol grip deformity” on AP radiographs, see Figure 58. Pistol grip deformity was first

described by Stulberg et al in 1975 who noted that it was present in 40% of patients who went onto develop OA of the hip.⁴⁹ It is recognised that pistol grip morphology is a description of what is now understood to be cam morphology. Although a subjective assessment of hip morphology determining the presence of pistol grip morphology Doherty et al found that the inter-observer reliability had an intraclass correlation coefficient of 0.88.²⁵⁵

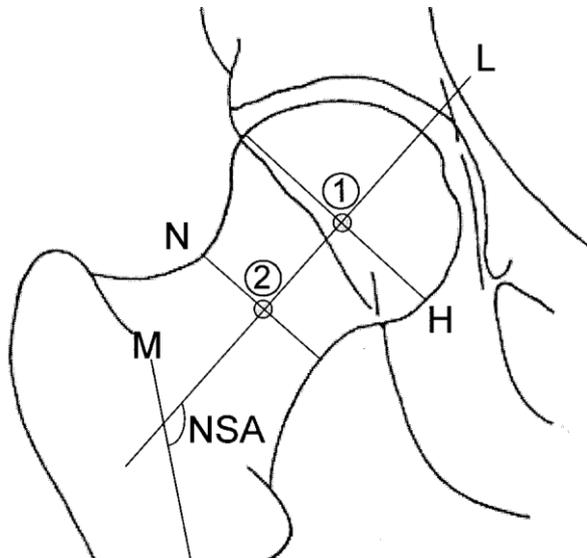
Figure 58 “Pistol Grip” Deformity (Source Stulberg et al 1975 ⁴⁹)



Femoral head neck ratios

Femoral head neck ratios were described by Doherty et al 2008²⁵⁵. Figure 59 is a diagrammatic representation of the how the femoral head neck ratio is calculated. A line is drawn along the axis of the femoral neck between the centre of the femoral head and the narrowest portion of the neck. Perpendicular to this line the maximal width of the femoral head and the minimal width of the neck are is calculated as a ratio of head/ neck. A ratio of <1.27 is evidence of cam morphology. The intraclass correlation coefficients for inter-observer reliability of head neck ratios is 0.84.

Figure 59 Diagrammatic representation of femoral head neck ratio (source Doherty et al 2008 ²⁵⁵)



Head ratio

Femoral head ratios were a method developed by Murray ⁴⁸. The head ratio is measured by drawing a line through the middle of the femoral neck and the middle of the axis between the greater and lesser trochanters. The ratio of the inferio medial head and the superiolateral head is measured. The larger the ratio the larger the cam morphology; see Figure 60

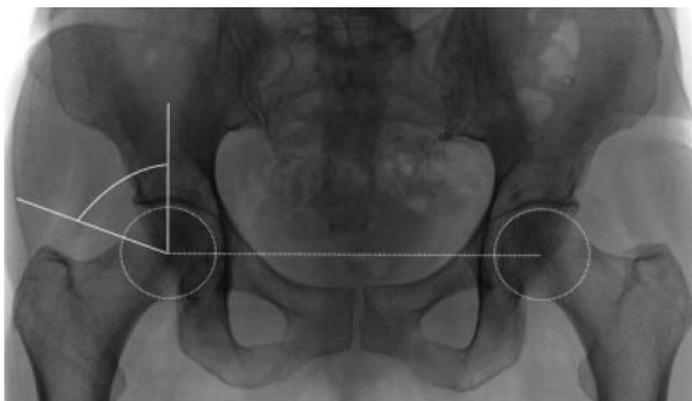
Figure 60 Femoral Head Ratio (source Dudda 2011 ³⁴²)



Impingement Angle

The impingement angle is measured by drawing a circle around the femoral head. An angle between the vertical axis of the radiograph, the centre of the femoral head and the point at which the head neck junction extends beyond the circle is measured. An angle $<70^\circ$ is a sign of cam morphology.³⁴²

Figure 61 The impingement angle (source Dudda 2011 ³⁴²)



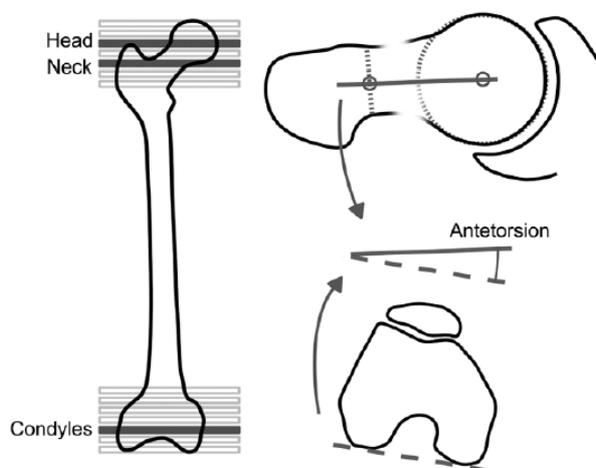
Neck Shaft Angle

The neck shaft angle is determined on an AP radiograph of the hip. It is an angle measured between the long axis of the femur and the axis of the femoral neck.³⁴³

Femoral Neck Antetorsion

Femoral neck antetorsion is a measure of the degree of twist of the femoral neck in the axial plane relative to the posterior condyles of the femur.⁴⁶ It is measured on cross sectional axial imaging by measuring the angle of the axis of the femoral neck relative to the axis of the posterior femoral condyles; see Figure 62.³⁹

Figure 62 Femoral Neck Antetorsion (Source Sutter et al 2012 ⁴⁶)

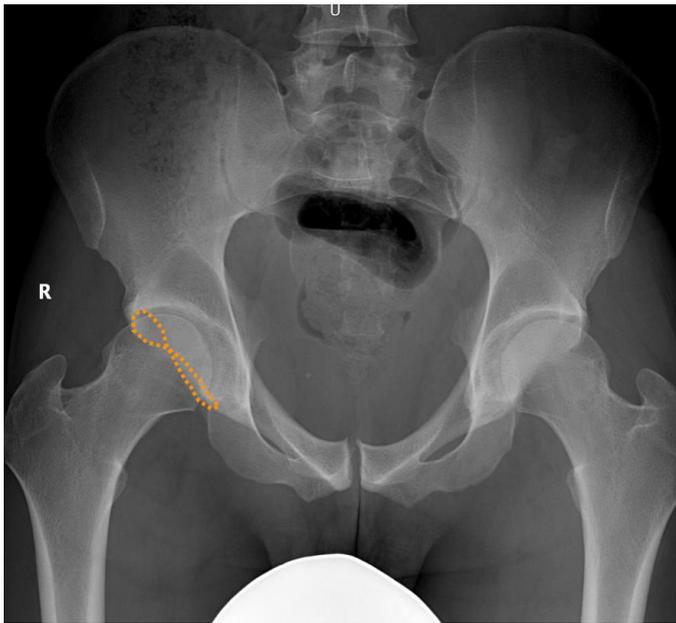


11.1.2 Measures of Acetabular Morphology

Cross Over Sign

This is a measure of acetabular retroversion on an AP radiograph without rotation or tilt.⁵⁸ It is determined by the crossing of the anterior and posterior walls of the acetabular margin to form a figure of 8; see Figure 63.

Figure 63 Cross over sign



Lateral Centre Edge Angle of Wiberg (CEA)

The centre edge angle (CEA) is a measure of lateral acetabular coverage.⁶⁵ It was initially described as an assessment of acetabular dysplasia. The CEA is determined by drawing a vertical line (perpendicular to the transverse axis of the pelvis) from the centre of the femoral head and measuring the angle to the rim of the acetabular sourcil. The axis of vertical line can be determined by drawing a line perpendicular to a line across the inferior point of the ischium or the axis of the centre of the 2 femoral heads.

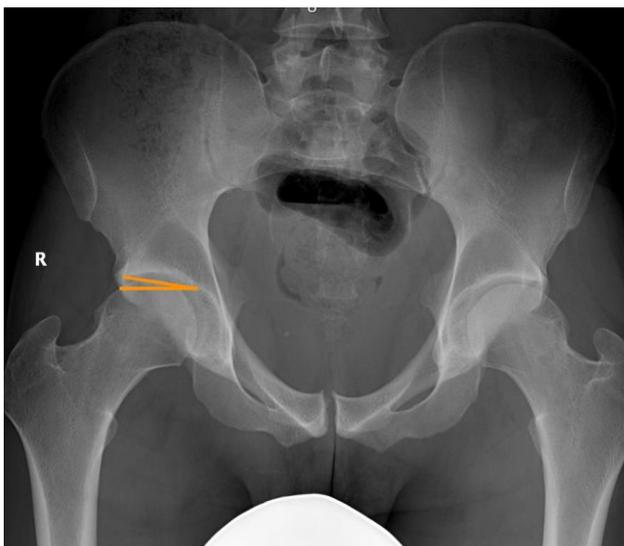
Figure 64 Centre Edge Angle



Tonnis Angle (acetabular inclination)

The Tonnis angle is a measure of the lateral inclination of the acetabular sourcil.⁶⁴ It is determined by measuring the angle between a line drawn parallel to the transverse pelvic axis and a line drawn between the inferiomedial and superiolateral aspects of the sourcil. An angle between 0-10degrees is considered normal.⁵⁸

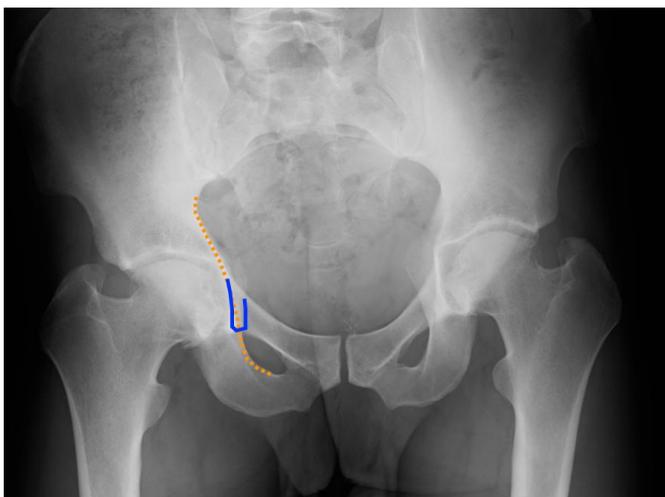
Figure 65 Tonnis angle



Coxa Profunda

Coxa profunda is a measure of global increased acetabular coverage. It is determined when the acetabular fossa is medial to the ilio ischial line; see Figure 66.⁵⁸

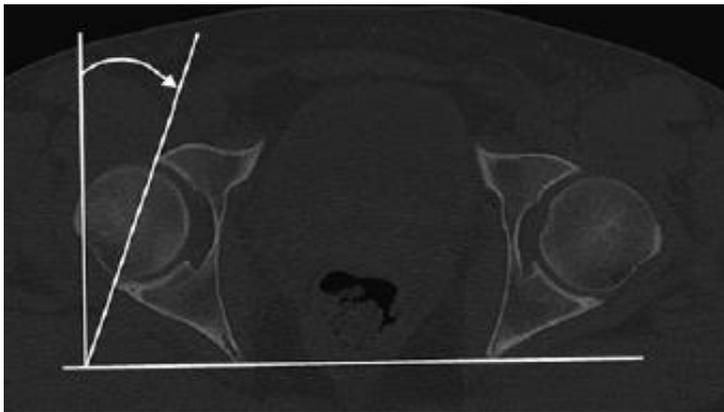
Figure 66 Coxa Profunda



Acetabular anteversion

Acetabular anteversion is measured on cross sectional imaging. It is measured on axial cuts of the pelvis. Anteversion can be measured at different levels in the coronal plane; for example the junction of the superior $\frac{1}{4}$ and 2nd $\frac{1}{4}$ of the femoral head. When described by Tonnis in 1999 the measure was described as being made on the slice of the pelvis where the femoral head and acetabulum were most congruent.³⁹ The posterior axis of the ischial spines is determined as a reference plane to correct for pelvic rotation, a perpendicular line to this is drawn, determining the sagittal plane of the pelvis, and the angle to the anterior and posterior rim of the acetabulum measured; see Figure 67.³⁹

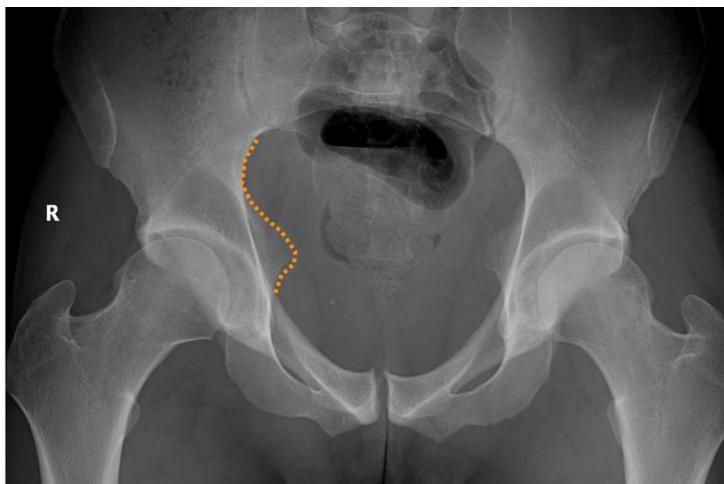
Figure 67 Acetabular Anteversion (Source Dandachli et al 2010¹⁹⁹)



Ischial Spine Sign

Ischial spine sign is an AP radiographic sign that indicates acetabular retroversion. It is determined only on an adequately centred AP radiograph.⁴⁵ It is present when the ischial spine is visible within the pelvic brim; see Figure 68.⁵⁸

Figure 68 Ischial Spine Sign

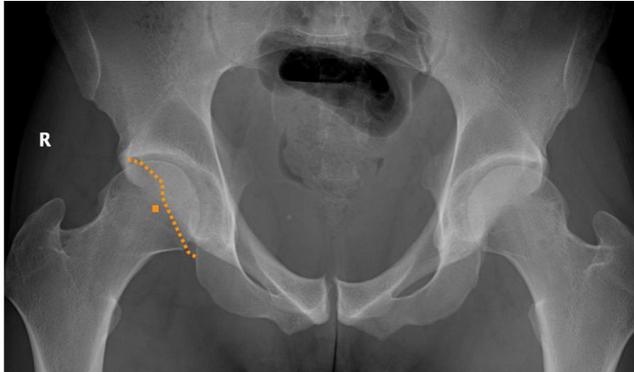


Posterior Wall Sign

Posterior wall sign is a measure of acetabular retroversion made on an AP radiograph. The radiograph must be appropriately centred without excessive pelvic tilt or rotation in order for the measure to be valid.¹³⁷ The sign is positive if the posterior wall of the acetabulum is medial to the centre of the femoral head;

see Figure 69. In the presence of cross over sign it indicated acetabular retroversion, in isolation it indicated posterior wall insufficiency.⁴⁵

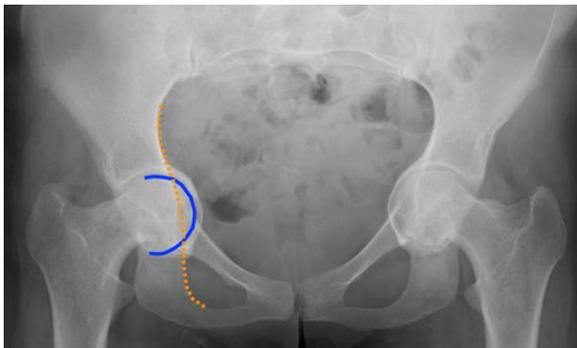
Figure 69 Posterior Wall Sign



Protrusio Acetabuli

Protrusio acetabuli is an AP radiographic measure of acetabular over coverage. The sign is present when the femoral head breaches the ilioischial line; see Figure 70.⁵⁸

Figure 70 Protrusio Acetabuli

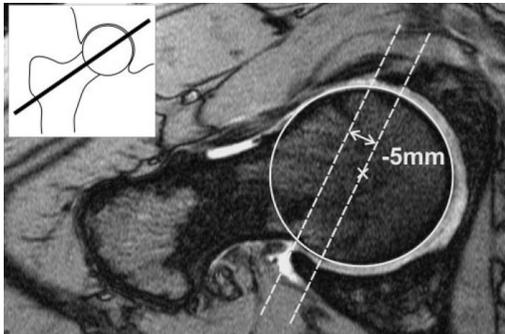


Acetabular Depth

Acetabular depth is a measure, in mm, of acetabular coverage. It is measured on cross sectional axial oblique (to line of femoral neck) imaging at the mid point of the femoral head. Depth of the acetabulum was defined by the distance between the line that connects the anterior and posterior acetabular rims and a parallel line

through the centre of the femoral head; see Figure 71.¹⁶ A negative measure is considered indicative of pincer morphology.

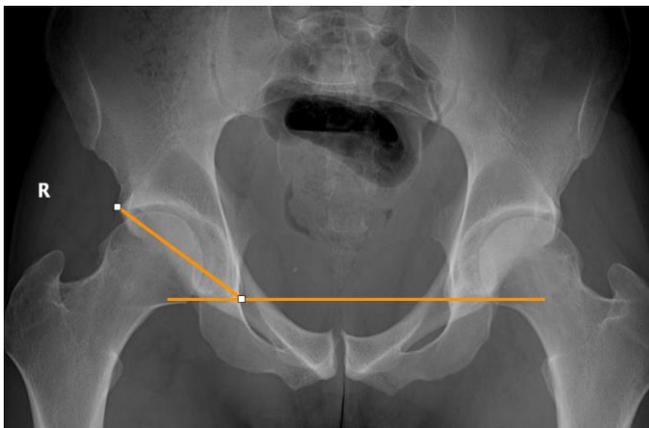
Figure 71 Acetabular Depth (Soruce Pffirman et al 2006 ¹⁶)



Sharps Angle

Similar to the Tonnis angle, Sharps angle is a measure of the lateral inclination of the acetabulum. It is measured between the transverse acetabular axis, the inferior aspect of the tear drop and the lateral edge of the sourcil; see Figure 72.

Figure 72 Sharps Angle

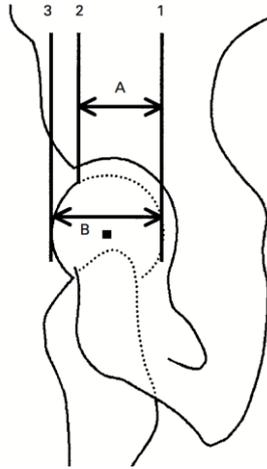


Anterior acetabular head index

Anterior acetabular head index is a measure of anterior over coverage made on a false profile view of the hip. It is determined by three line: 1) a verticle line crossing the posterior aspect of the femoral head, 2) a vericle line through the anterior aspect of the acetabulum, 3) a verticle line through the anterior border of

the femoral head; see Figure 73. Anterior acetabular head index is defined by the ratio of the distance between lines first and second line, and the distance between the first and third lines. This ratio is converted into a percentage.³⁴⁴

Figure 73 Anterior acetabular head index = $(A/B) \times 100$ (Source Chosa et al 2003 ³⁴⁴)



11.2 Chapter 4; additional material

11.2.1 Coordinates of the ROC curve for α angles to determine the presence of cam morphology.

Coordinates of the Curve			
Test Result Variable(s)	Positive if Greater Than or Equal To ^a	Sensitivity	1 - Specificity
12 o'clock	33.0000	1.000	1.000
	34.5000	1.000	.992
	35.5000	1.000	.983
	36.5000	1.000	.975
	37.5000	.983	.925
	38.5000	.967	.875
	39.5000	.900	.775
	40.5000	.817	.667
	41.5000	.783	.550
	42.5000	.750	.467
	43.5000	.650	.392
	44.5000	.550	.325
	45.5000	.450	.242
	46.5000	.367	.167
	47.5000	.333	.100
	48.5000	.333	.075
	49.5000	.317	.058
	51.0000	.300	.050
	52.5000	.283	.042
	53.5000	.283	.033
	54.5000	.233	.033
	61.0000	.233	.025
	69.5000	.217	.025
	72.5000	.200	.025
	73.5000	.183	.025
	75.0000	.167	.025
	77.5000	.150	.025
	80.0000	.150	.017
	81.5000	.133	.017
	82.5000	.117	.008
84.5000	.067	.000	
87.5000	.017	.000	
90.0000	.000	.000	
1 o'clock	36.0000	1.000	1.000
	37.5000	1.000	.992
	38.5000	1.000	.983
	39.5000	1.000	.975
	40.5000	1.000	.967
	41.5000	.983	.958
	42.5000	.983	.933
	43.5000	.967	.875
	44.5000	.933	.833
	45.5000	.917	.800
	46.5000	.917	.775
	47.5000	.883	.742
	48.5000	.883	.700
	49.5000	.883	.650
	50.5000	.883	.592
	51.5000	.850	.567
	52.5000	.817	.533
	53.5000	.817	.508
	54.5000	.800	.492
	55.5000	.783	.442
	56.5000	.767	.392
57.5000	.767	.358	
59.0000	.750	.333	
60.5000	.733	.308	

	61.5000	.733	.292
	62.5000	.733	.275
	63.5000	.733	.258
	64.5000	.717	.225
	65.5000	.717	.200
	67.0000	.683	.175
	68.5000	.667	.167
	69.5000	.617	.150
	70.5000	.583	.150
	71.5000	.550	.142
	73.0000	.500	.125
	74.5000	.467	.108
	75.5000	.433	.108
	76.5000	.383	.100
	77.5000	.350	.083
	78.5000	.317	.067
	79.5000	.283	.042
	81.0000	.267	.042
	82.5000	.250	.042
	83.5000	.233	.033
	84.5000	.183	.033
	85.5000	.167	.033
	86.5000	.150	.025
	87.5000	.100	.017
	88.5000	.083	.008
	89.5000	.050	.008
	91.5000	.050	.000
	95.0000	.033	.000
	98.0000	.000	.000
2 o'clock	29.0000	1.000	1.000
	33.0000	1.000	.992
	36.5000	1.000	.983
	38.0000	1.000	.967
	39.5000	1.000	.942
	40.5000	1.000	.925
	41.5000	1.000	.883
	42.5000	.967	.858
	43.5000	.967	.800
	44.5000	.967	.783
	45.5000	.967	.758
	46.5000	.967	.700
	47.5000	.967	.667
	48.5000	.950	.600
	49.5000	.933	.558
	50.5000	.933	.533
	51.5000	.917	.492
	52.5000	.883	.475
	53.5000	.883	.425
	54.5000	.883	.417
	55.5000	.850	.392
	56.5000	.817	.375
	57.5000	.800	.350
	58.5000	.783	.308
	59.5000	.767	.283
	60.5000	.767	.225
	61.5000	.733	.217
	62.5000	.683	.192
	63.5000	.617	.175
	64.5000	.550	.167
	65.5000	.533	.150
	66.5000	.500	.125
	67.5000	.500	.108
	68.5000	.467	.092
	69.5000	.433	.092
	70.5000	.417	.075
	71.5000	.383	.058
	72.5000	.350	.042
	73.5000	.300	.033
	75.5000	.267	.025
	77.5000	.217	.025

	78.5000	200	.025
	80.0000	167	.017
	81.5000	133	.017
	83.5000	117	.008
	85.5000	100	.000
	86.5000	.083	.000
	88.0000	.050	.000
	90.0000	.033	.000
	93.5000	.017	.000
	97.0000	.000	.000
3 o'clock	29.0000	1.000	1.000
	30.5000	.983	.975
	31.5000	.983	.967
	32.5000	.983	.950
	33.5000	.983	.942
	34.5000	.967	.900
	35.5000	.950	.858
	36.5000	.933	.817
	37.5000	.917	.733
	38.5000	.900	.708
	39.5000	.900	.633
	40.5000	.850	.567
	41.5000	.833	.533
	42.5000	.817	.475
	43.5000	.767	.408
	44.5000	.750	.350
	45.5000	.733	.300
	46.5000	.733	.292
	47.5000	.733	.275
	48.5000	.700	.233
	49.5000	.683	.167
	50.5000	.667	.158
	51.5000	.650	.125
	52.5000	.583	.092
	53.5000	.583	.075
	54.5000	.550	.067
	55.5000	.517	.050
	56.5000	.483	.050
	57.5000	.467	.050
	58.5000	.433	.050
	59.5000	.400	.033
	60.5000	.383	.033
	62.0000	.333	.033
	64.5000	.250	.025
	66.5000	.233	.025
	67.5000	.217	.025
	68.5000	.217	.017
	69.5000	.183	.017
	70.5000	.183	.000
	71.5000	.167	.000
	72.5000	.150	.000
	73.5000	.133	.000
	74.5000	.117	.000
	75.5000	.083	.000
	76.5000	.050	.000
	81.5000	.033	.000
	86.5000	.017	.000
	88.0000	.000	.000
7 o'clock	31.0000	1.000	1.000
	32.5000	1.000	.992
	33.5000	1.000	.983
	34.5000	1.000	.950
	35.5000	.967	.942
	36.5000	.917	.858
	37.5000	.850	.700
	38.5000	.767	.608
	39.5000	.667	.467
	40.5000	.517	.383
	41.5000	.367	.292
	42.5000	.300	.192

	43.5000	.217	.125
	44.5000	.167	.092
	45.5000	.033	.067
	46.5000	.017	.025
	47.5000	.000	.008
	49.0000	.000	.000
mean of alpha angles from 12 to 3 o'clock	34.8000	1.000	1.000
	36.5500	1.000	.992
	37.9000	1.000	.983
	38.9000	1.000	.975
	39.4000	1.000	.967
	39.6500	1.000	.950
	39.9000	1.000	.942
	40.4000	1.000	.925
	40.9000	1.000	.917
	41.2500	1.000	.908
	41.6500	.983	.892
	41.9000	.983	.883
	42.4000	.983	.850
	42.9000	.983	.842
	43.1500	.983	.817
	43.4000	.983	.800
	43.6500	.983	.783
	43.9000	.983	.767
	44.1500	.983	.750
	44.4000	.983	.742
	44.6500	.983	.717
	44.9000	.967	.717
	45.1500	.967	.708
	45.4000	.967	.675
	45.6500	.950	.650
	45.9000	.950	.617
	46.1500	.950	.608
	46.4000	.950	.592
	46.6500	.950	.575
	47.0500	.950	.558
	47.4000	.950	.525
	47.7500	.950	.492
	48.1500	.950	.483
	48.4000	.933	.467
	48.6500	.917	.442
	48.9000	.917	.425
	49.1500	.883	.417
	49.4000	.883	.400
	49.6500	.883	.383
	50.0500	.883	.375
50.4000	.867	.375	
50.6500	.850	.367	
50.9000	.850	.342	
51.1500	.850	.325	
51.4000	.850	.317	
51.6500	.833	.300	
51.9000	.817	.283	
52.1500	.817	.275	
52.6500	.767	.275	
53.1500	.750	.267	
53.5500	.750	.258	
54.1500	.750	.233	
54.6500	.733	.233	
54.9000	.733	.225	
55.1500	.700	.208	
55.4000	.700	.200	
55.6500	.700	.192	
56.0500	.700	.175	
56.4000	.667	.150	
56.6500	.667	.133	
56.9000	.650	.133	
57.2500	.617	.133	
57.6500	.617	.108	
57.9000	.600	.108	

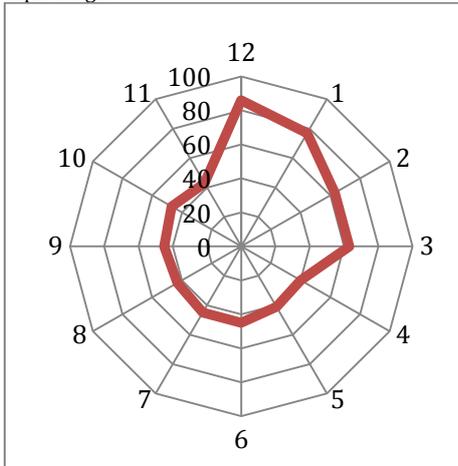
	58.1500	.600	.100
	58.5500	.600	.083
	58.9000	.583	.083
	59.1500	.567	.075
	59.4000	.533	.067
	59.6500	.517	.067
	59.9000	.500	.067
	60.1500	.483	.058
	60.4000	.467	.058
	60.6500	.467	.050
	60.9000	.467	.042
	61.1500	.450	.042
	61.6500	.417	.042
	62.1500	.400	.042
	62.9000	.400	.033
	63.6500	.383	.033
	63.9000	.367	.033
	64.2500	.350	.033
	64.6500	.333	.025
	65.0500	.333	.017
	65.5500	.317	.017
	66.4000	.300	.017
	67.4000	.283	.017
	68.9000	.283	.008
	70.1500	.267	.008
	70.6500	.250	.008
	71.1500	.233	.008
	71.8000	.217	.008
	72.4000	.183	.008
	73.0000	.183	.000
	73.6500	.167	.000
	74.9000	.150	.000
	76.5000	.133	.000
	77.5000	.117	.000
	78.1500	.100	.000
	79.1500	.083	.000
	80.5000	.067	.000
	81.1500	.050	.000
	81.6500	.033	.000
	82.1500	.017	.000
	83.3000	.000	.000

The test result variable(s): 12 o'clock, 1 o'clock, 2 o'clock, 3 o'clock, 7 o'clock, mean of alpha angles from 12 to 3 o'clock has at least one tie between the positive actual state group and the negative actual state group.

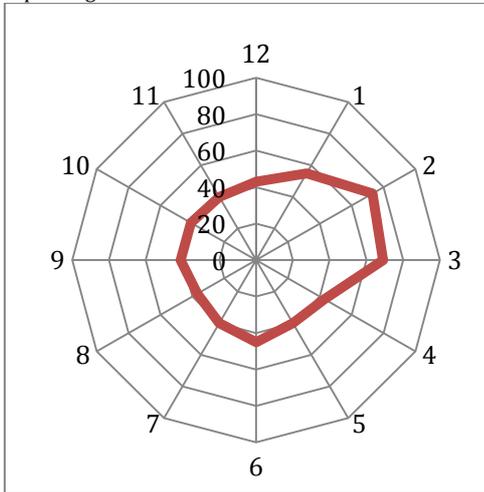
a. The smallest cutoff value is the minimum observed test value minus 1, and the largest cutoff value is the maximum observed test value plus 1. All the other cutoff values are the averages of two consecutive ordered observed test values.

11.2.2 Chapter 4; Radar Plots for cam morphology cases

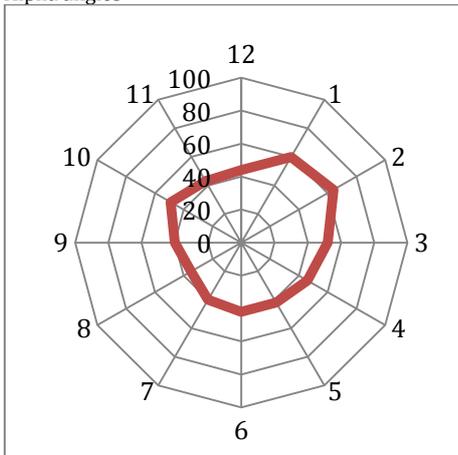
Cam Case 1
Alpha angles



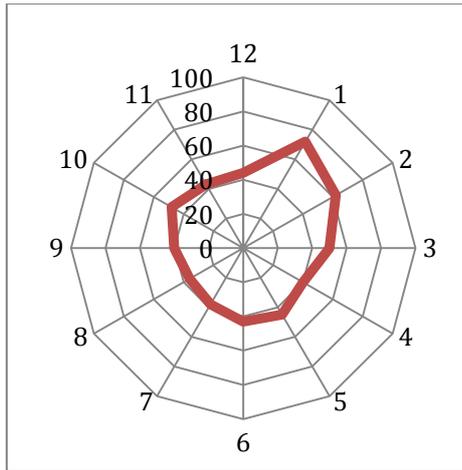
Cam Case 2
Alpha angles



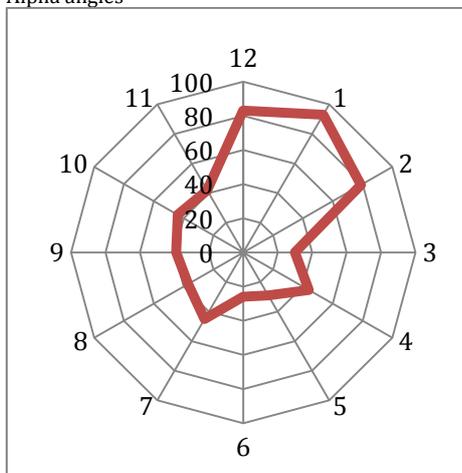
Cam Case 3
Alpha angles



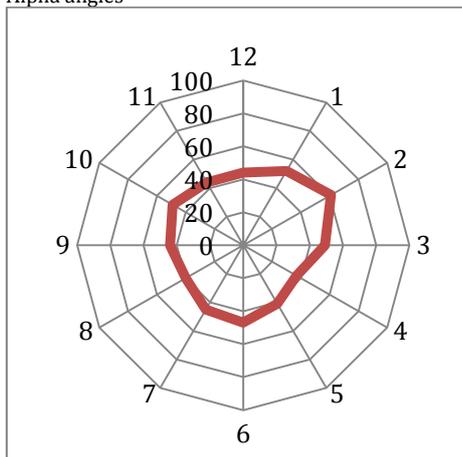
Cam Case 4
Alpha angles



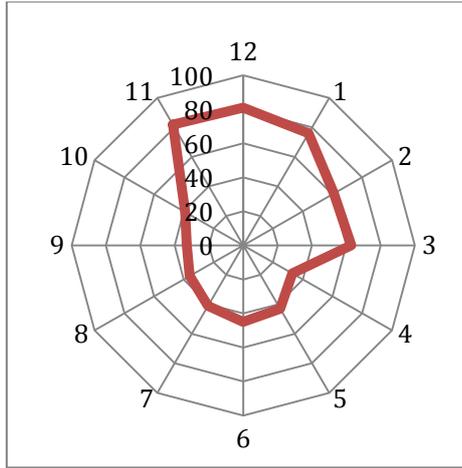
Cam Case 5
Alpha angles



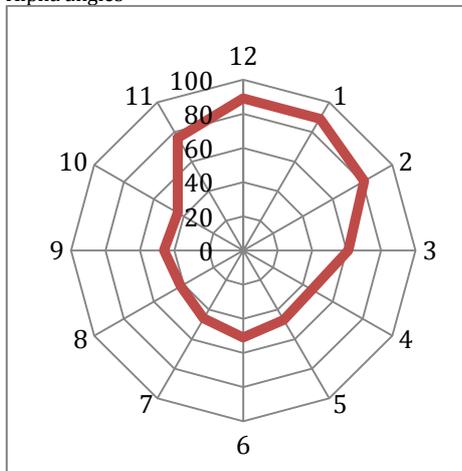
Cam Case 6
Alpha angles



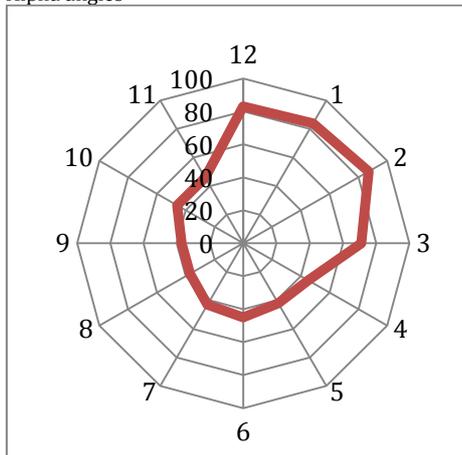
Cam Case 7
Alpha angles



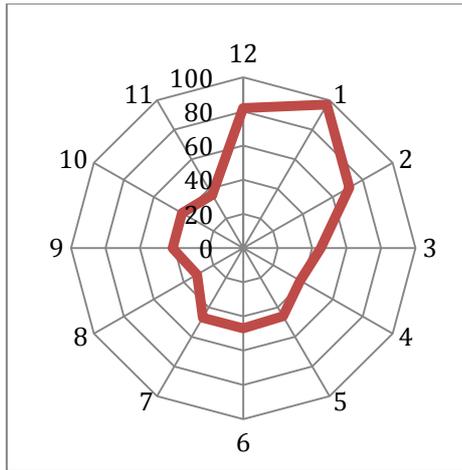
Cam Case 8
Alpha angles



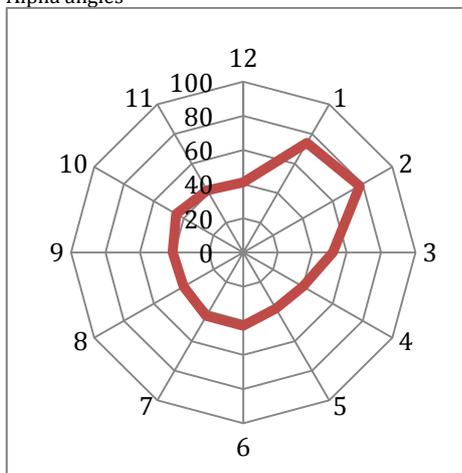
Cam Case 9
Alpha angles



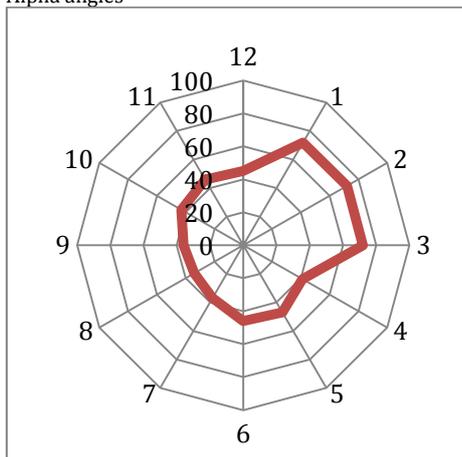
Cam Case 10
Alpha angles



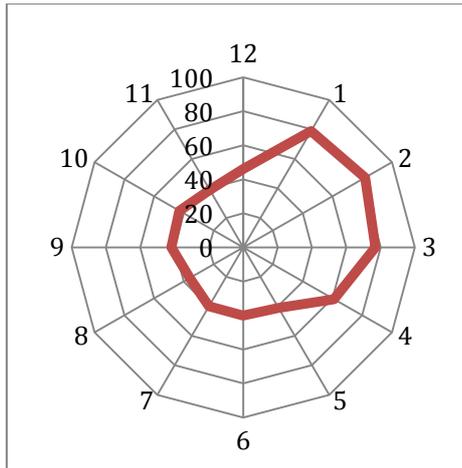
Cam Case 11
Alpha angles



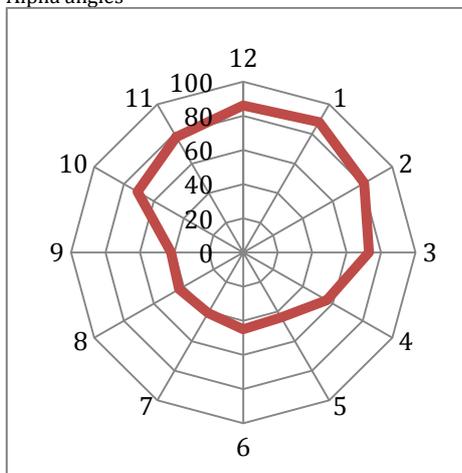
Cam Case 12
Alpha angles



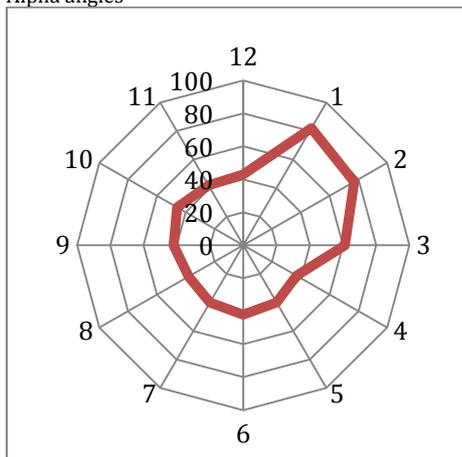
Cam Case 13
Alpha angles



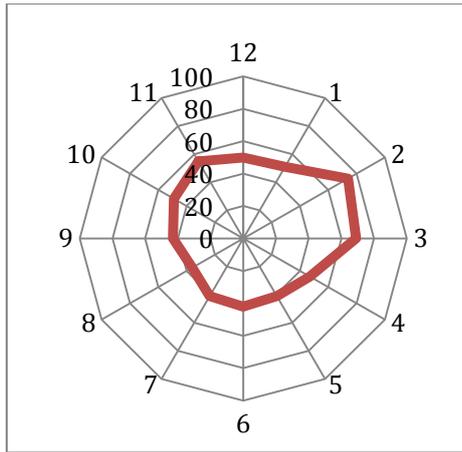
Cam Case 14
Alpha angles



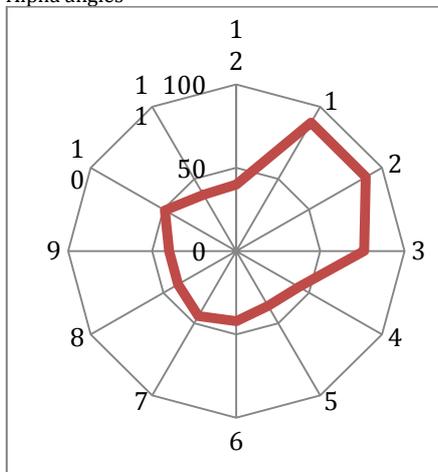
Cam Case 15
Alpha angles



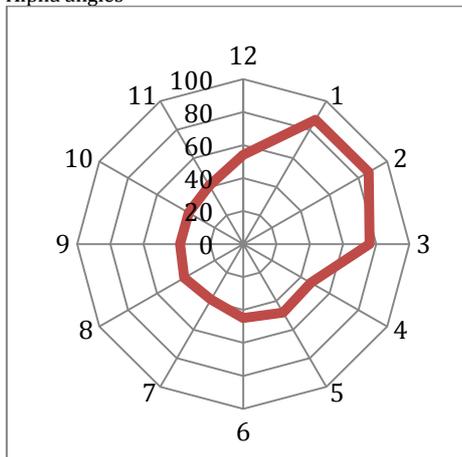
Cam Case 16
Alpha angles



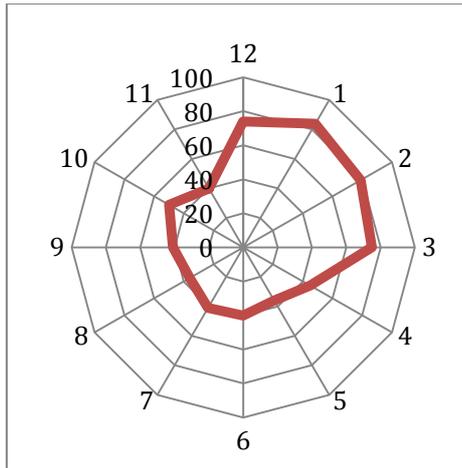
Cam Case 17
Alpha angles



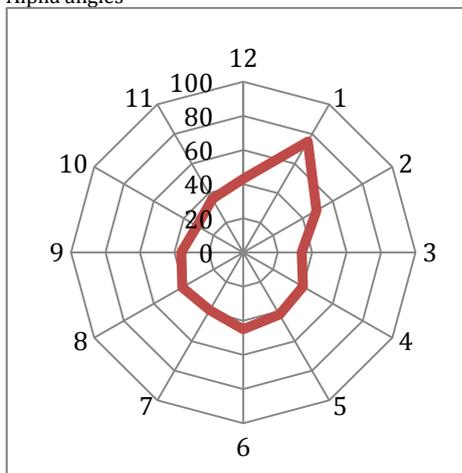
Cam Case 18
Alpha angles



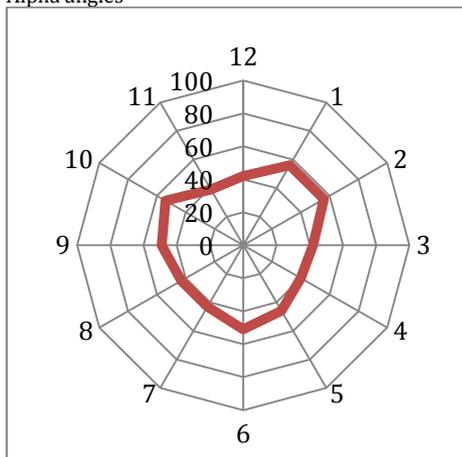
Cam Case 19
Alpha angles



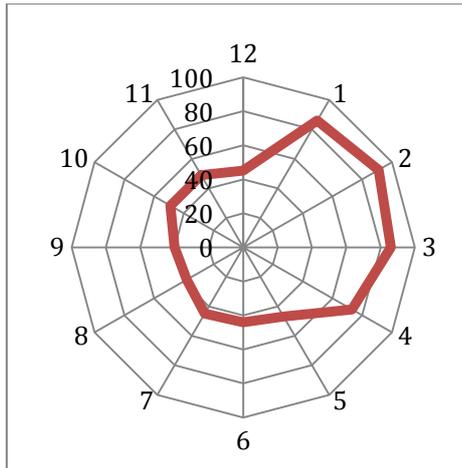
Cam Case 20
Alpha angles



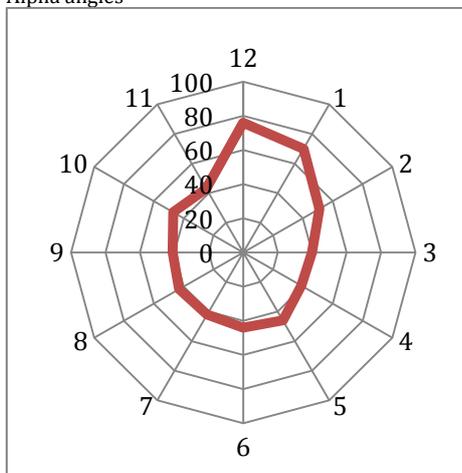
Cam Case 21
Alpha angles



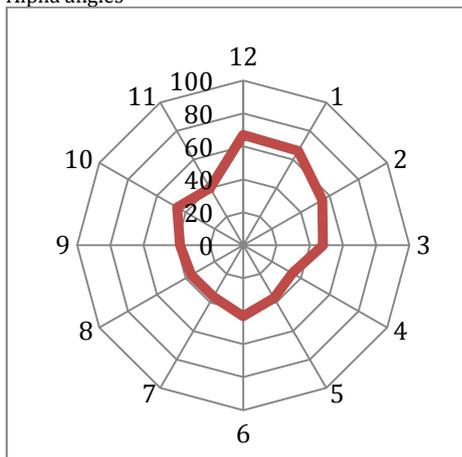
Cam Case 22
Alpha angles



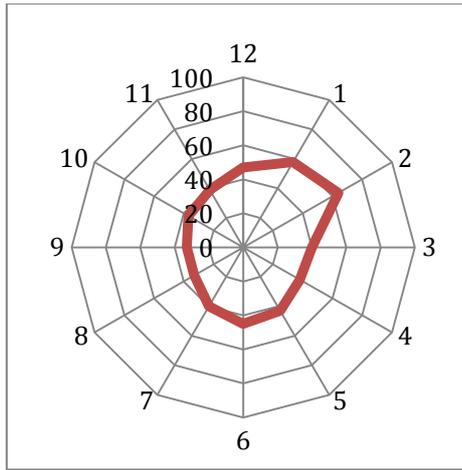
Cam Case 23
Alpha angles



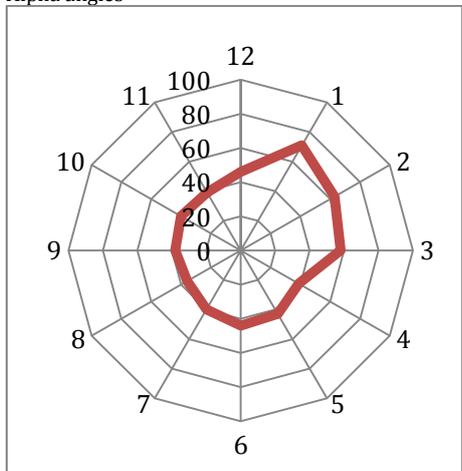
Cam Case 24
Alpha angles



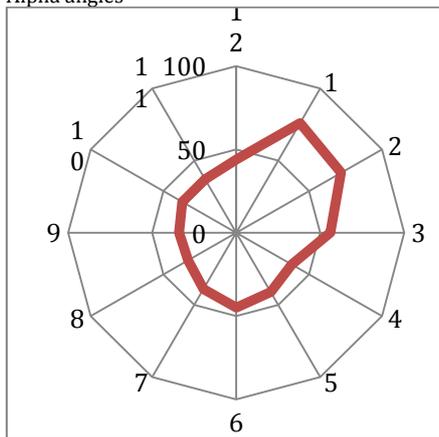
Cam Case 25
Alpha angles



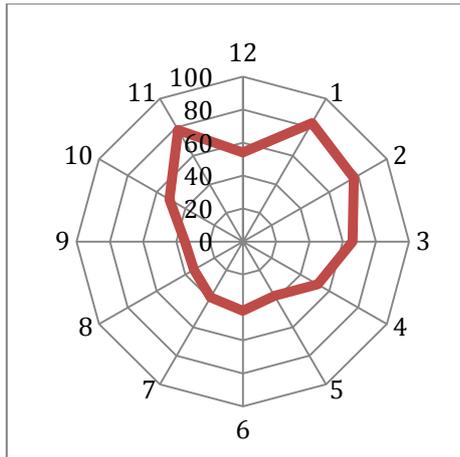
Cam Case 26
Alpha angles



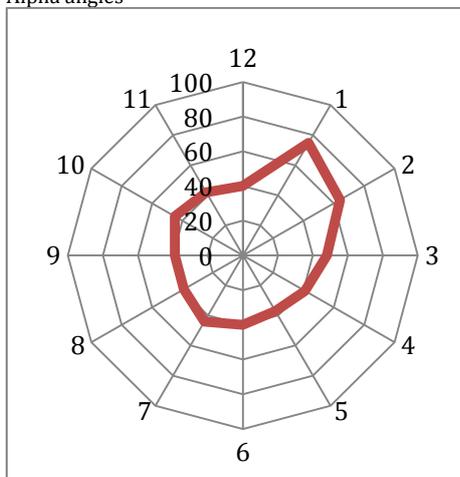
Cam Case 27
Alpha angles



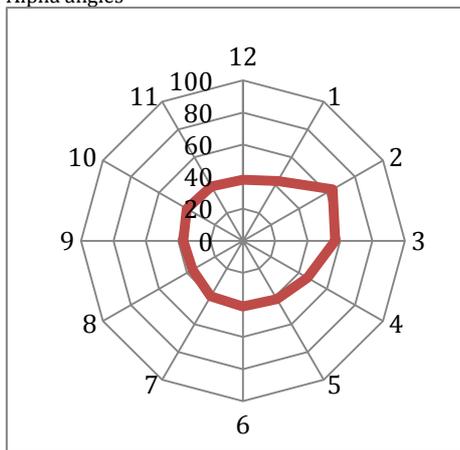
Cam Case 28
Alpha angles



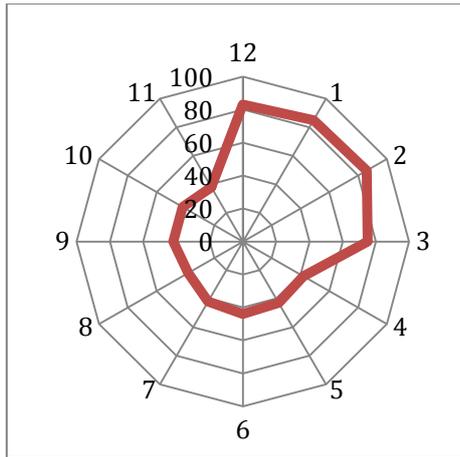
Cam Case 29
Alpha angles



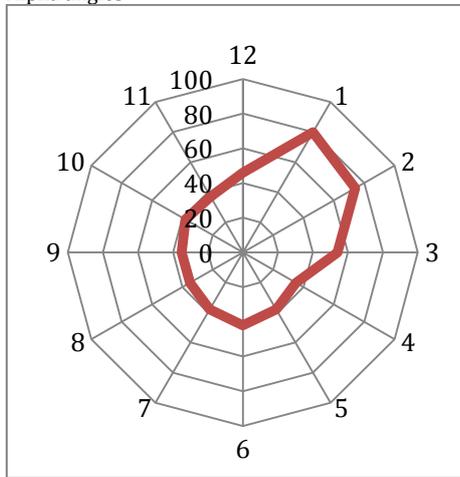
Cam Case 30
Alpha angles



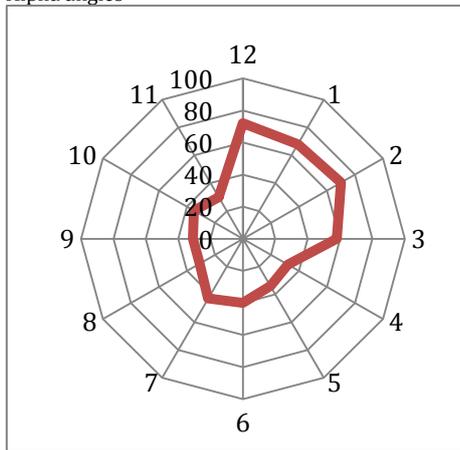
Cam Case 31
Alpha angles



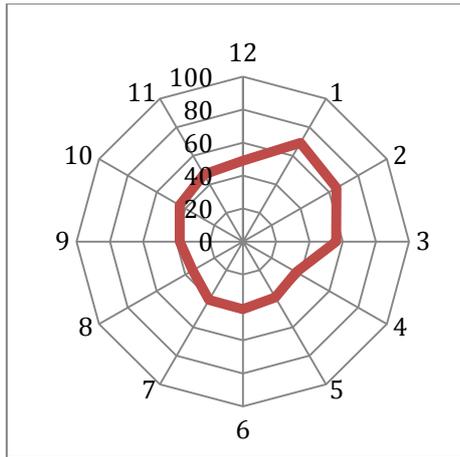
Cam Case 32
Alpha angles



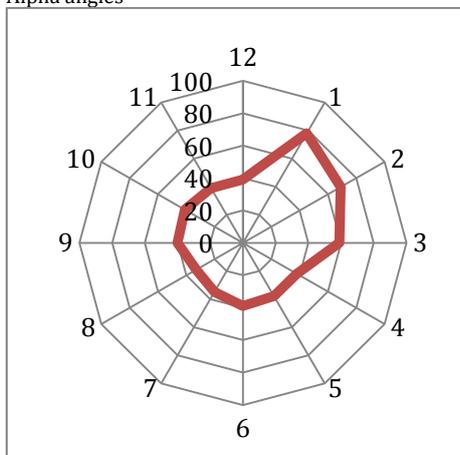
Cam Case 33
Alpha angles



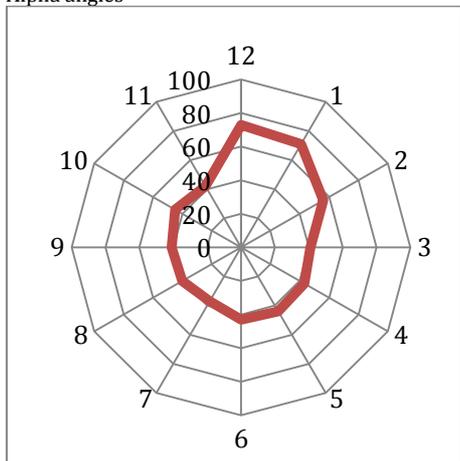
Cam Case 34
Alpha angles



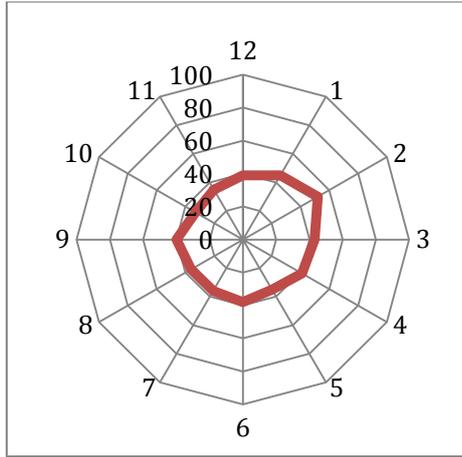
Cam Case 35
Alpha angles



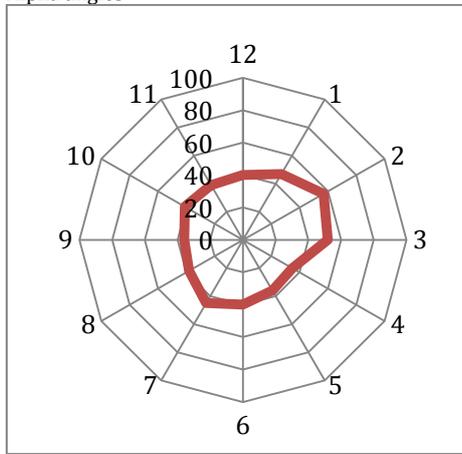
Cam Case 36
Alpha angles



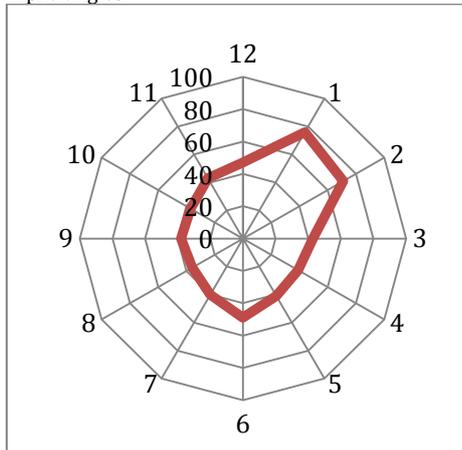
Cam Case 37
Alpha angles



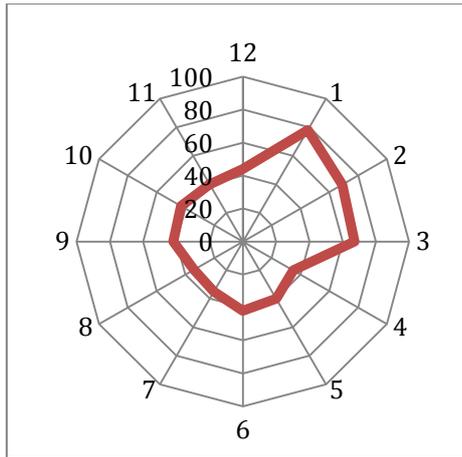
Cam Case 38
Alpha angles



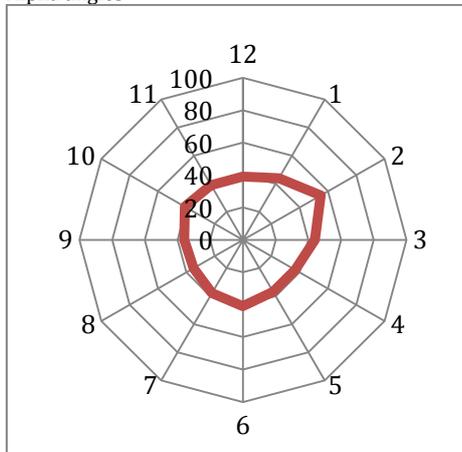
Cam Case 39
Alpha angles



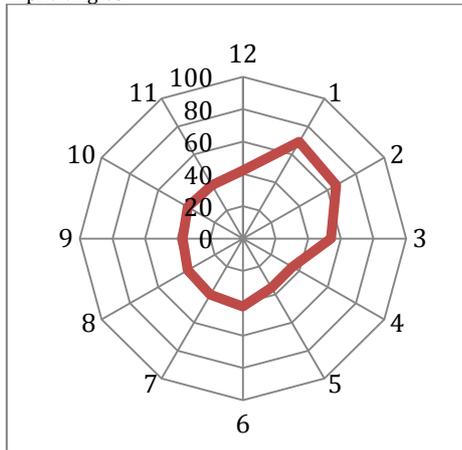
Cam Case 40
Alpha angles



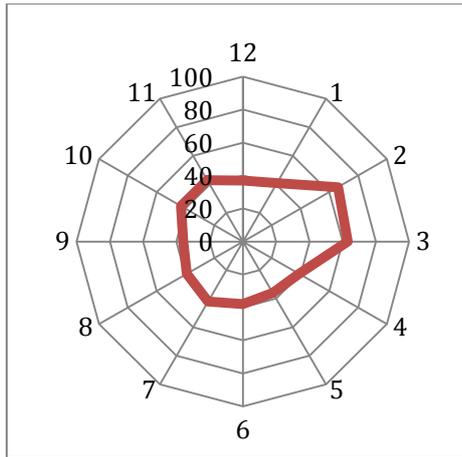
Cam Case 41
Alpha angles



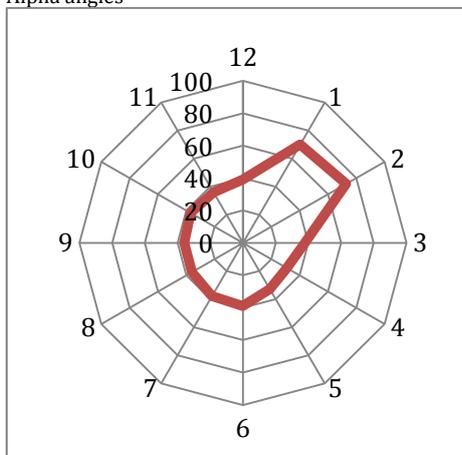
Cam Case 42
Alpha angles



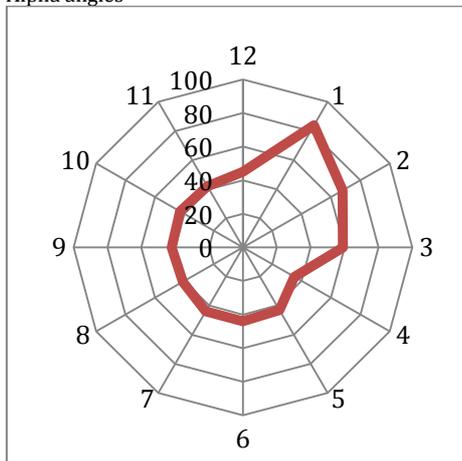
Cam Case 43
Alpha angles



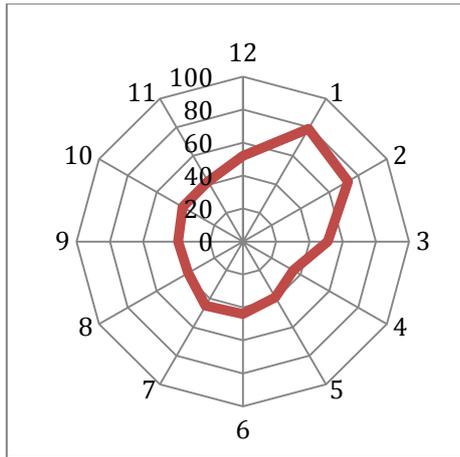
Cam Case 44
Alpha angles



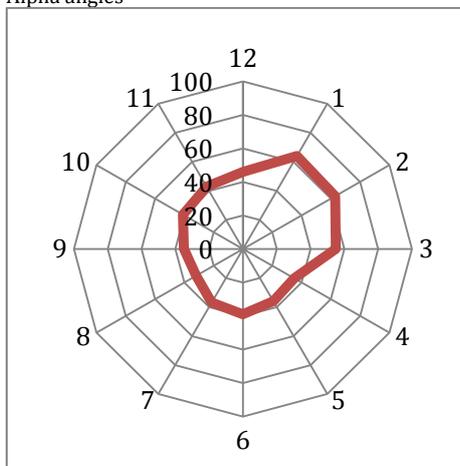
Cam Case 45
Alpha angles



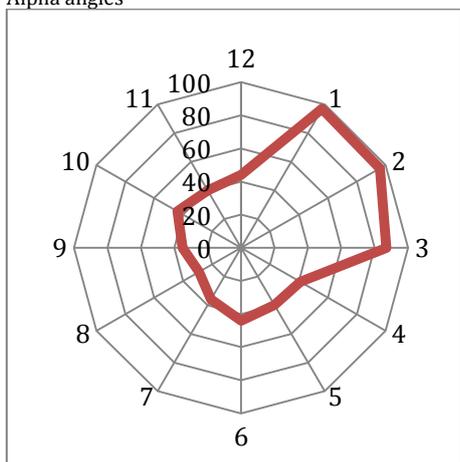
Cam Case 46
Alpha angles



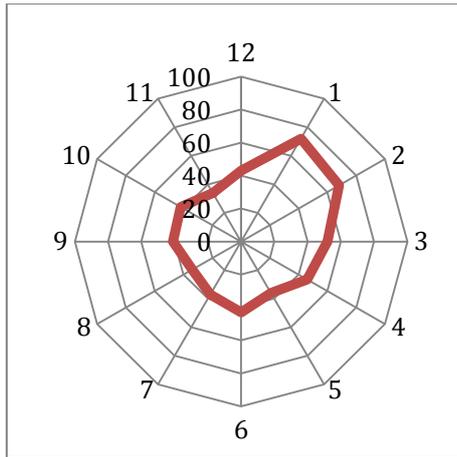
Cam Case 47
Alpha angles



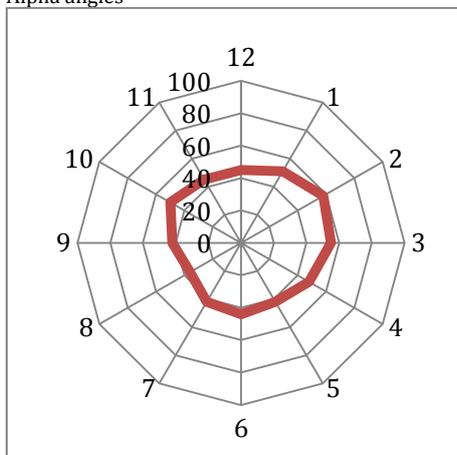
Cam Case 48
Alpha angles



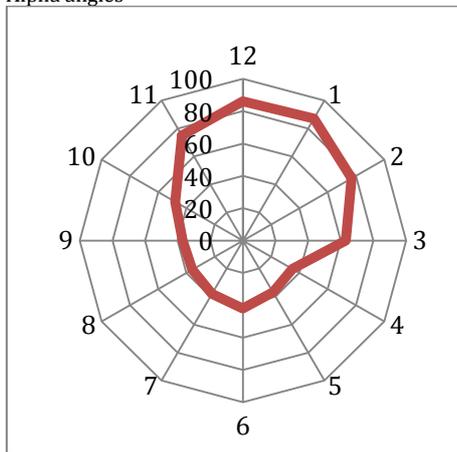
Cam Case 49
Alpha angles



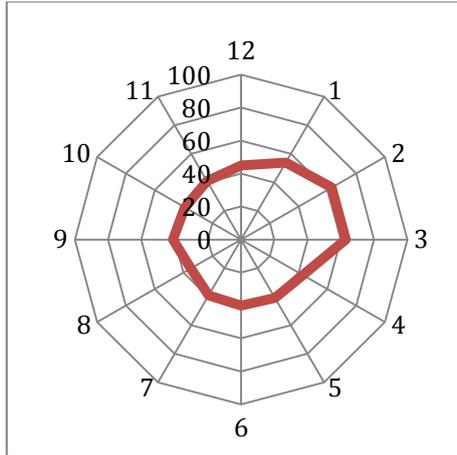
Cam Case 50
Alpha angles



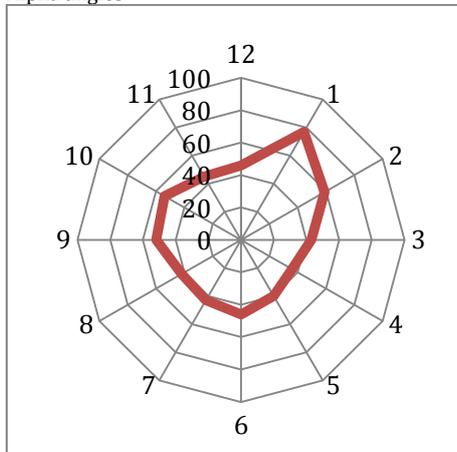
Cam Case 51
Alpha angles



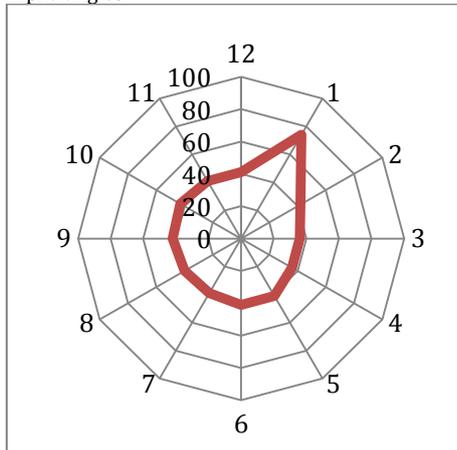
Cam Case 52
Alpha angles



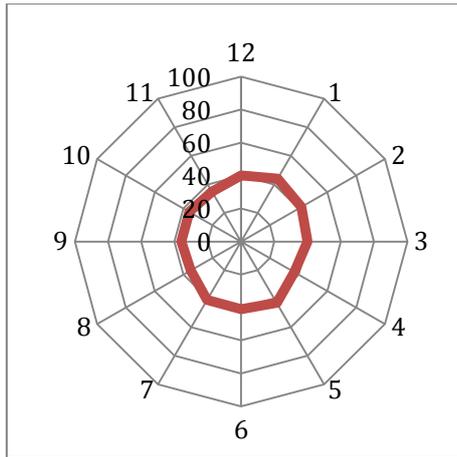
Cam Case 53
Alpha angles



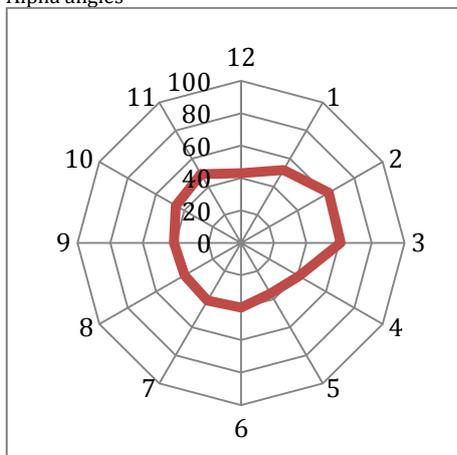
Cam Case 54
Alpha angles



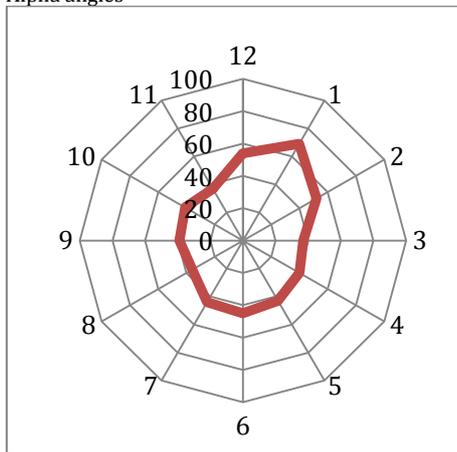
Cam Case 55
Alpha angles



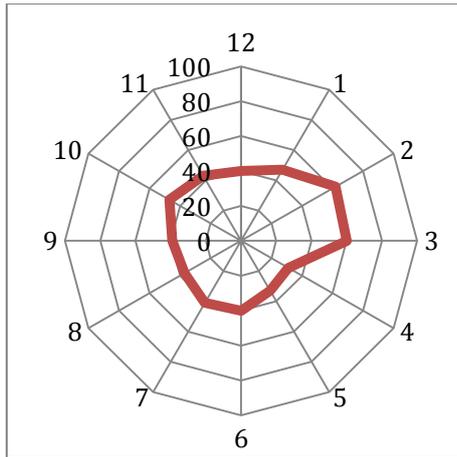
Cam Case 56
Alpha angles



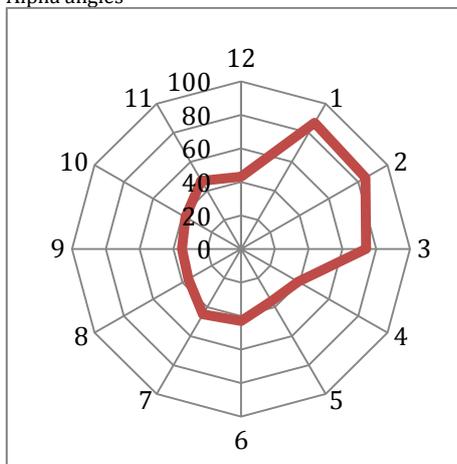
Cam Case 57
Alpha angles



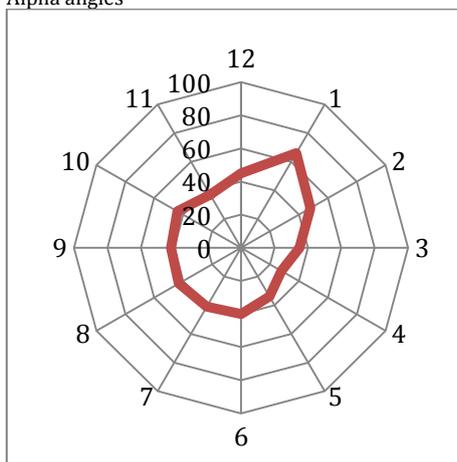
Cam Case 58
Alpha angles



Cam Case 59
Alpha angles



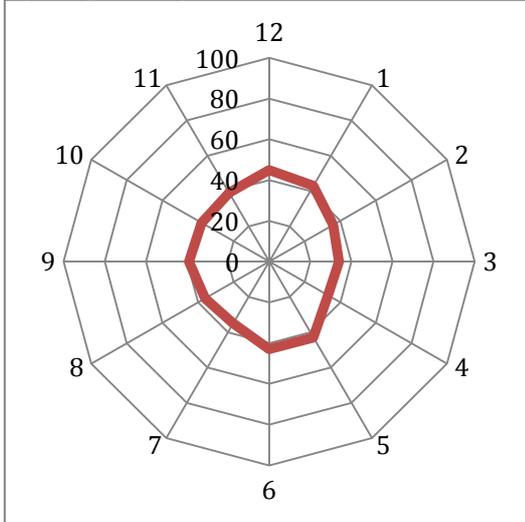
Cam Case 60
Alpha angles



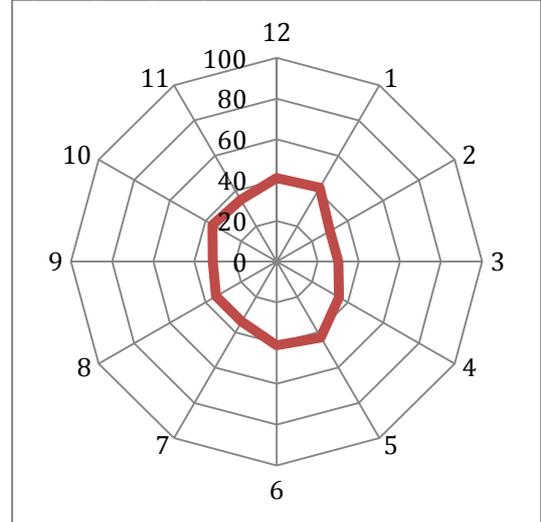
11.2.3 Chapter 4; Radar Plots for cam morphology controls

Cam Control 1

Alpha angles left hip

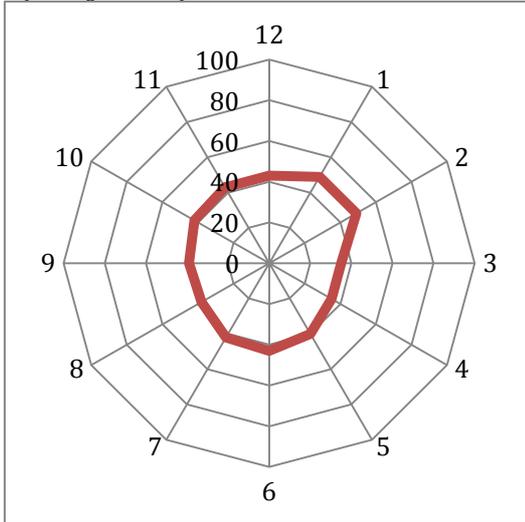


Alpha angles right hip

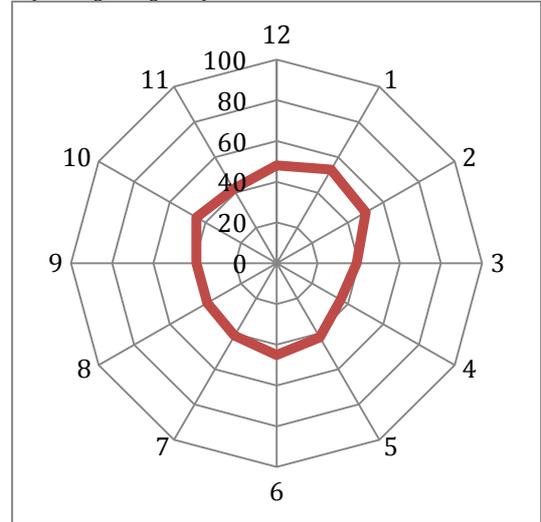


Cam Control 2

Alpha angles left hip

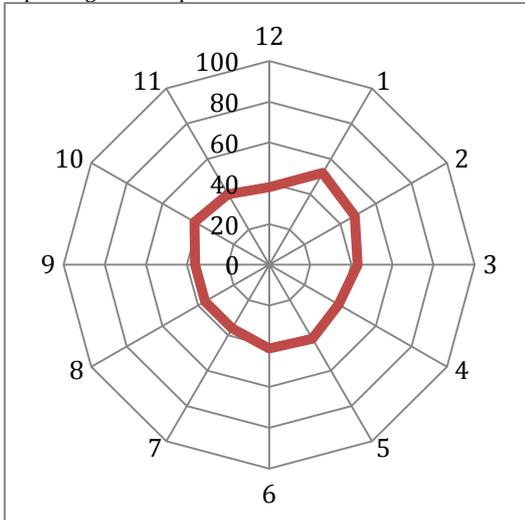


Alpha angles right hip

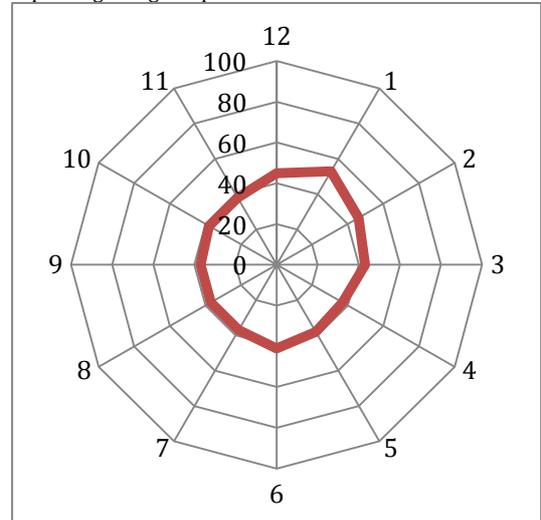


Cam Control 3

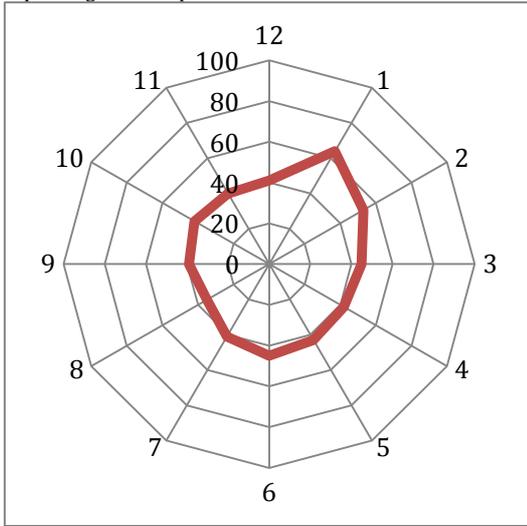
Alpha angles left hip



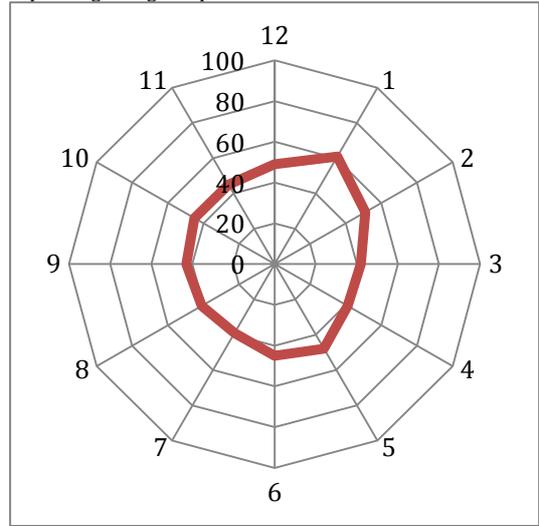
Alpha angles right hip



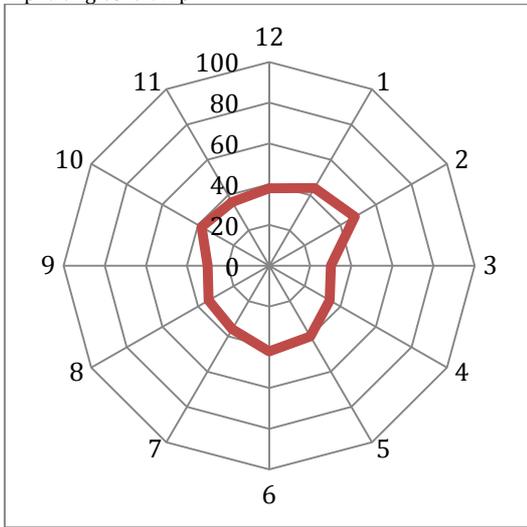
Cam Control 4
Alpha angles left hip



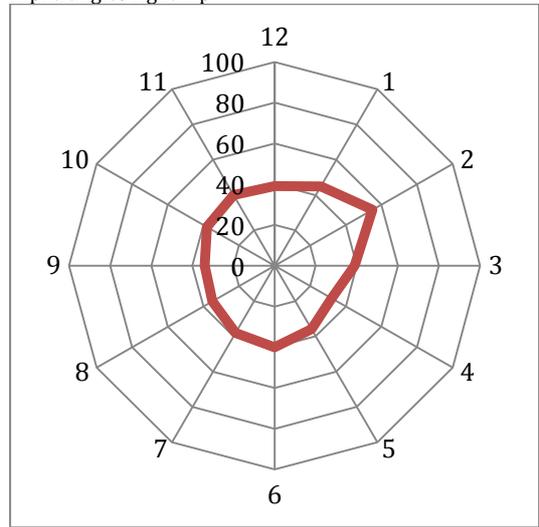
Alpha angles right hip



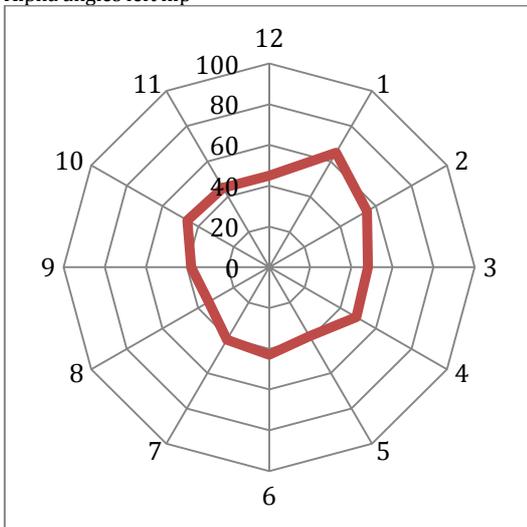
Cam Control 5
Alpha angles left hip



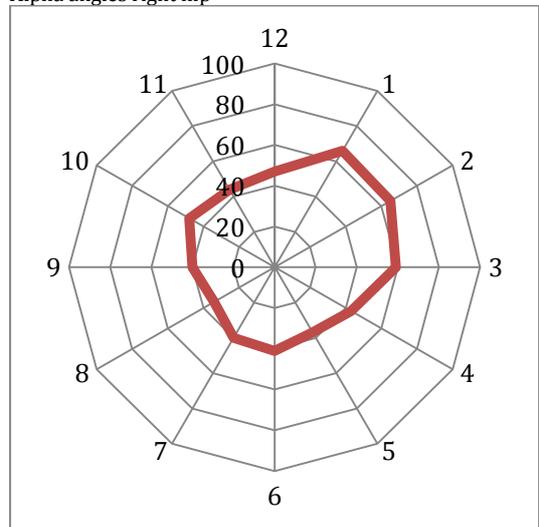
Alpha angles right hip



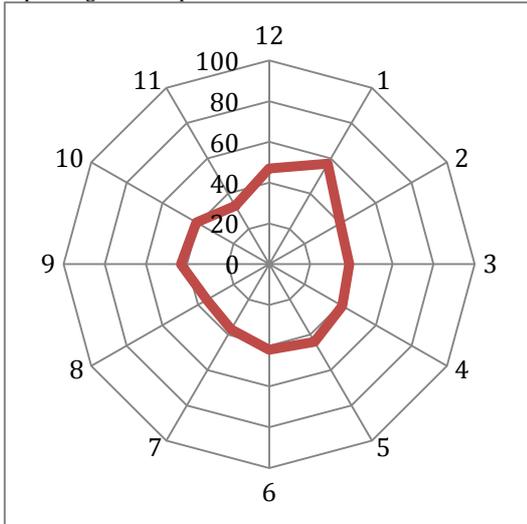
Cam Control 6
Alpha angles left hip



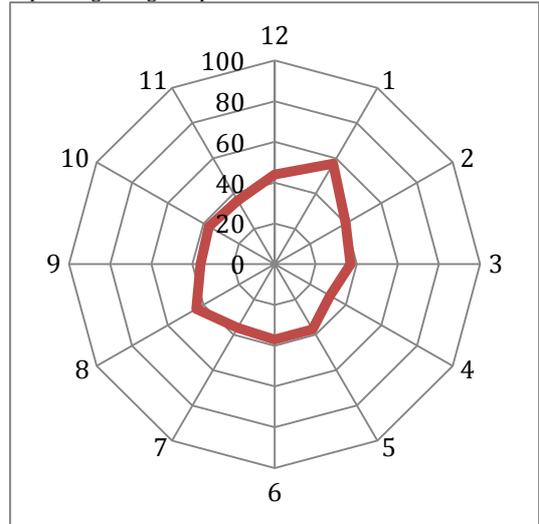
Alpha angles right hip



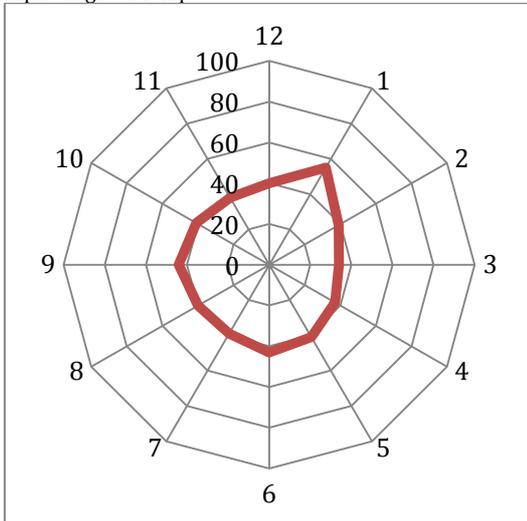
Cam Control 7
Alpha angles left hip



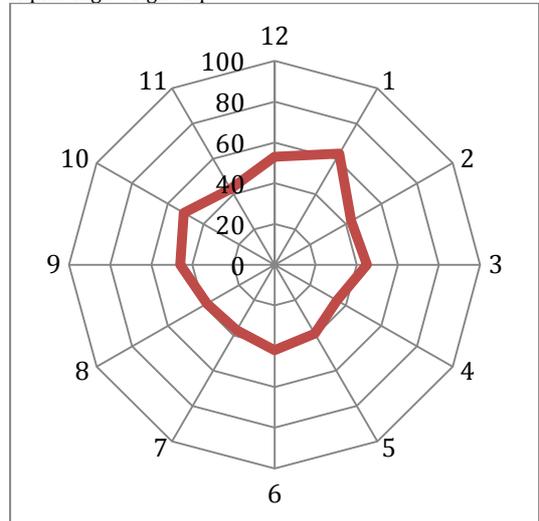
Alpha angles right hip



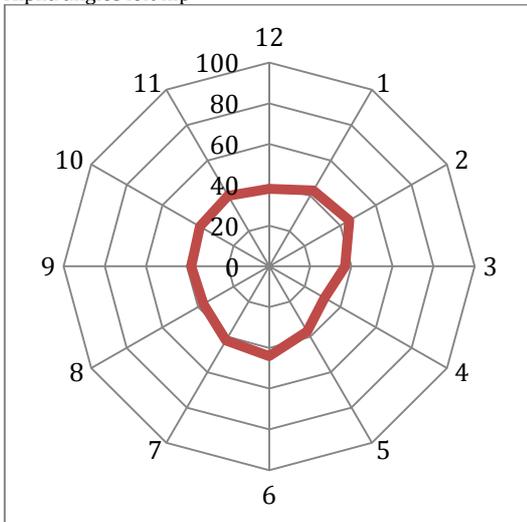
Cam Control 8
Alpha angles left hip



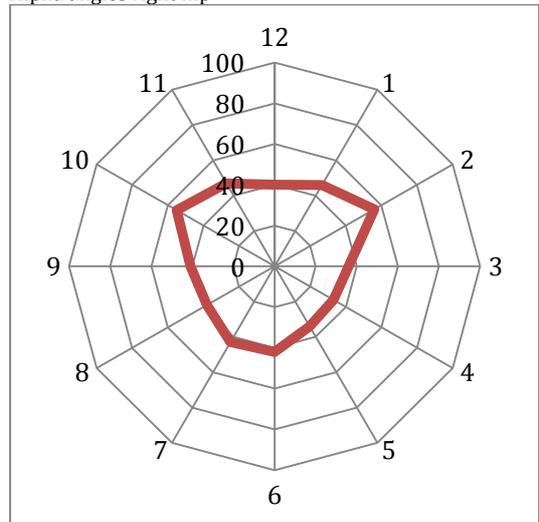
Alpha angles right hip



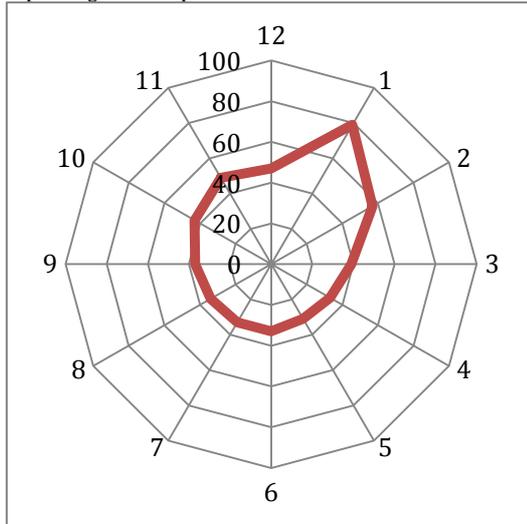
Cam Control 9
Alpha angles left hip



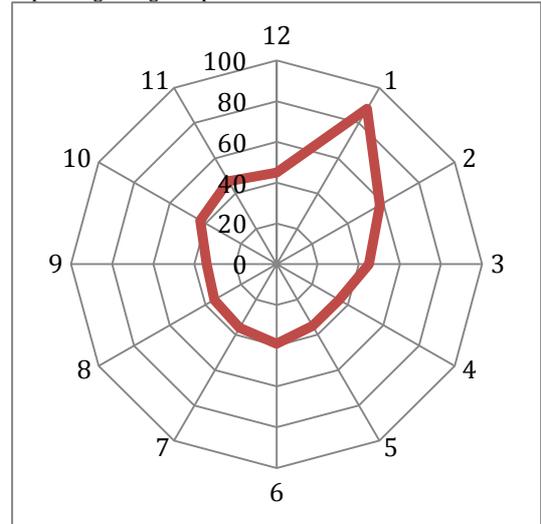
Alpha angles right hip



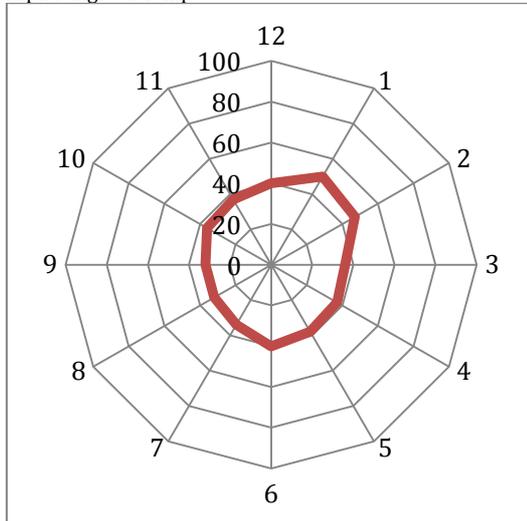
Cam Control 10
Alpha angles left hip



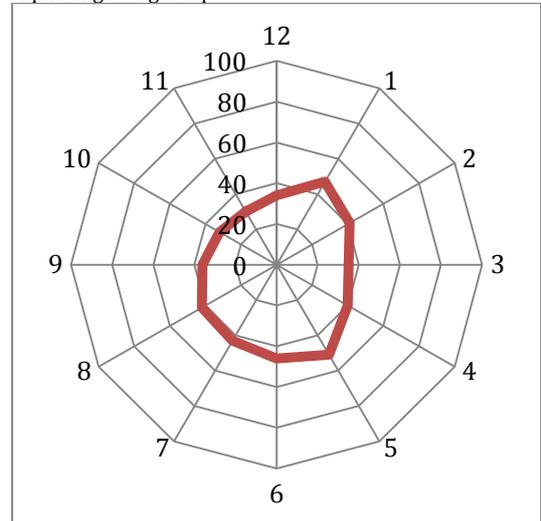
Alpha angles right hip



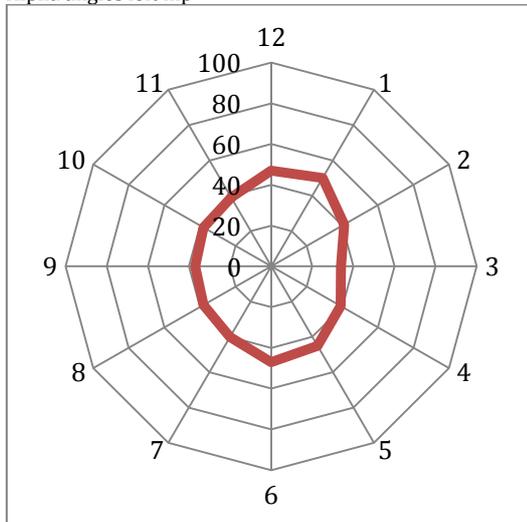
Cam Control 11
Alpha angles left hip



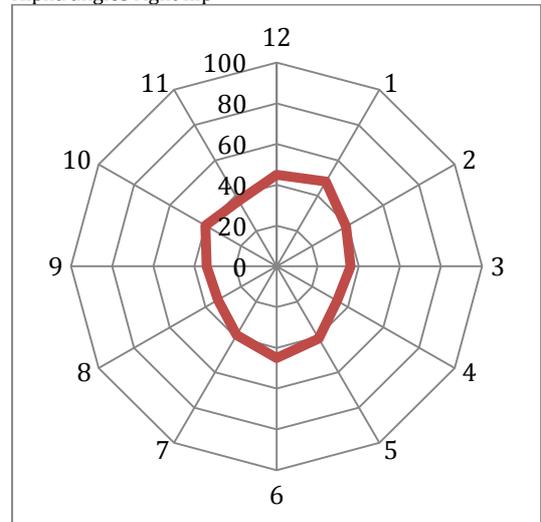
Alpha angles right hip



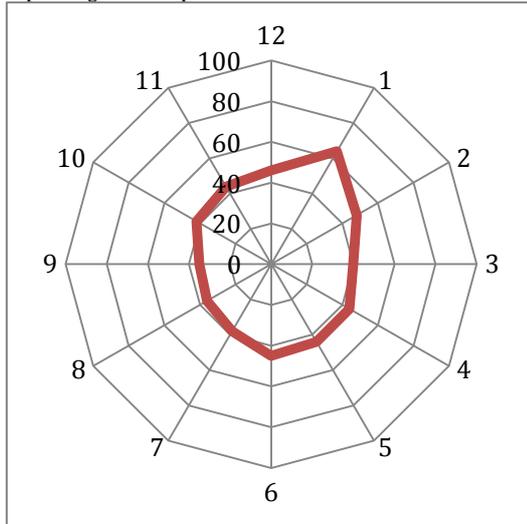
Cam Control 12
Alpha angles left hip



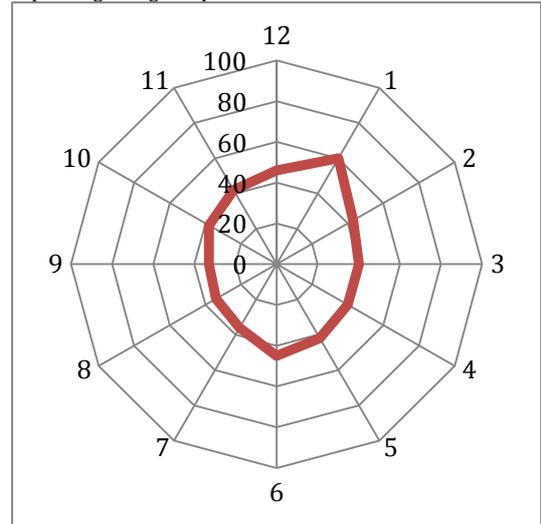
Alpha angles right hip



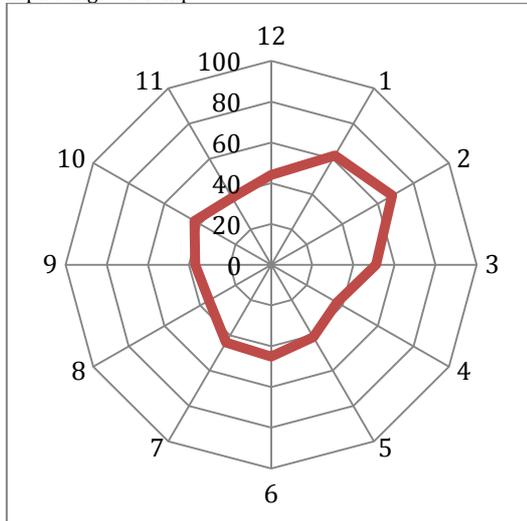
Cam Control 13
Alpha angles left hip



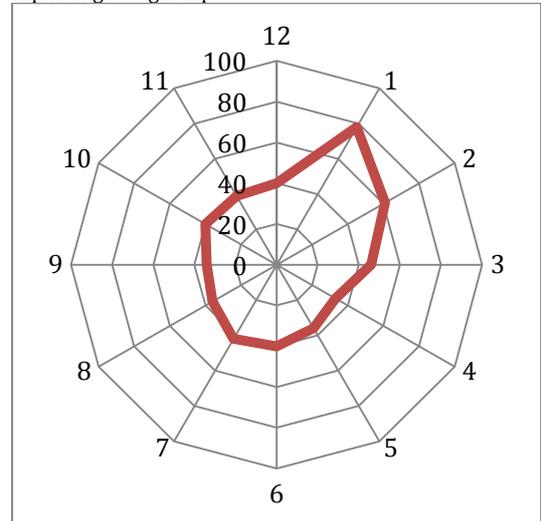
Alpha angles right hip



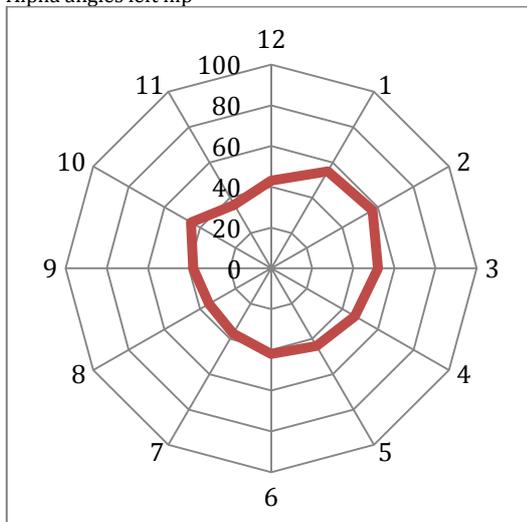
Cam Control 14
Alpha angles left hip



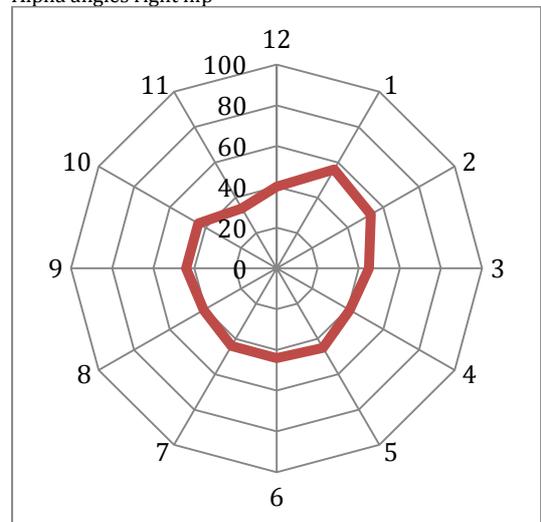
Alpha angles right hip



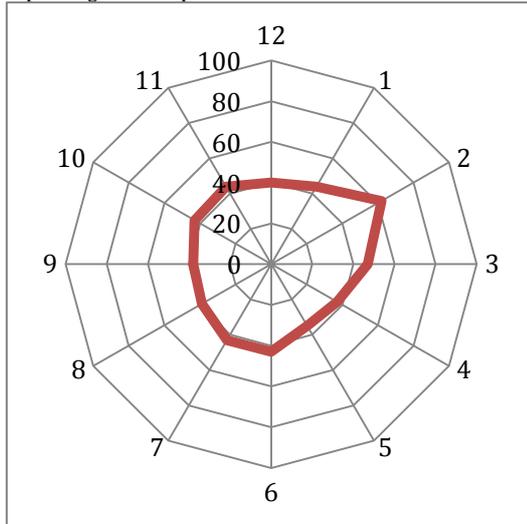
Cam Control 15
Alpha angles left hip



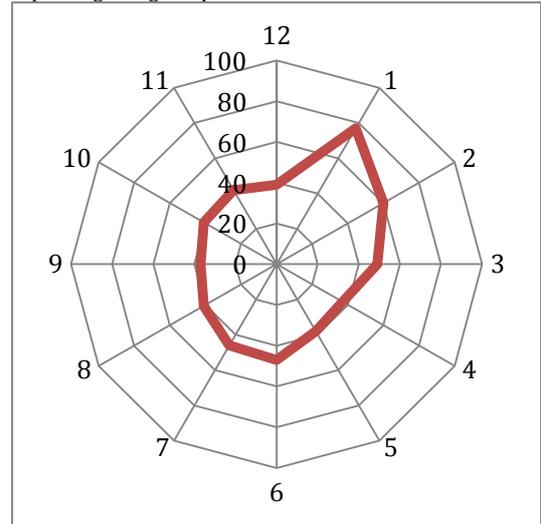
Alpha angles right hip



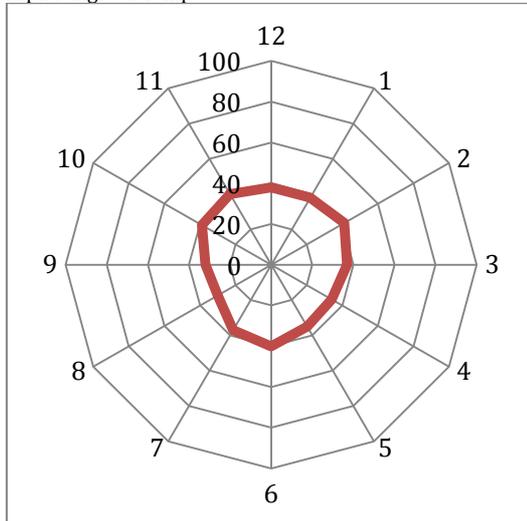
Cam Control 16
Alpha angles left hip



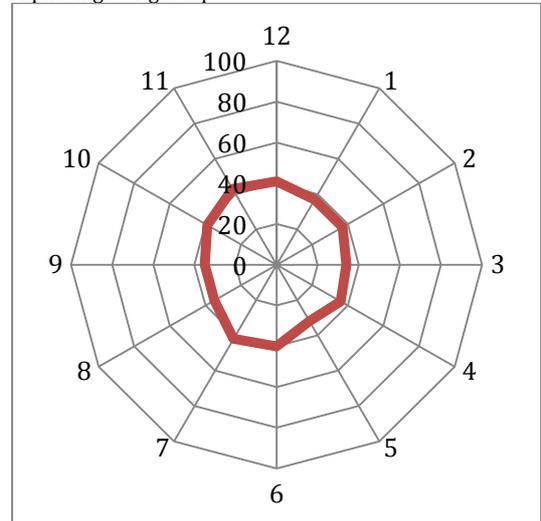
Alpha angles right hip



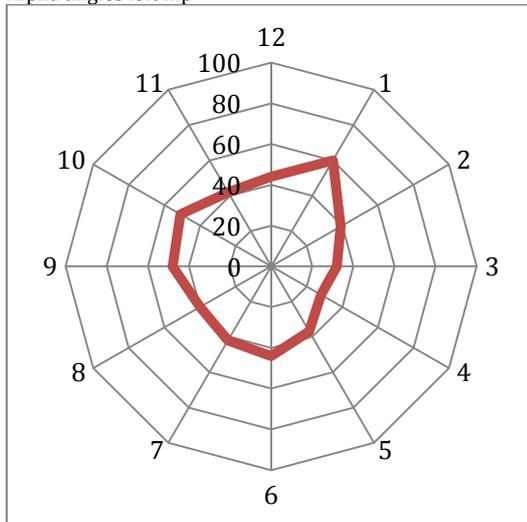
Cam Control 17
Alpha angles left hip



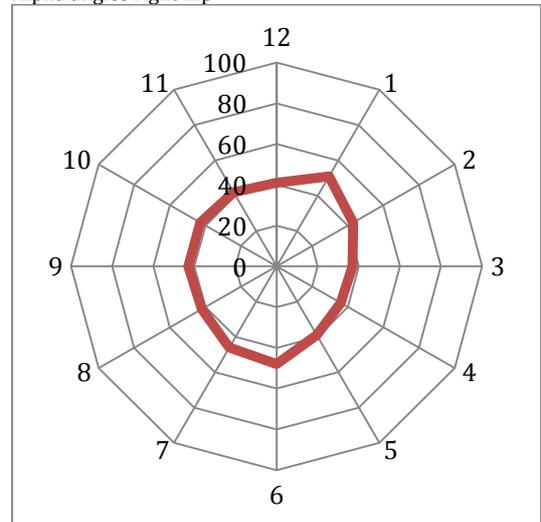
Alpha angles right hip



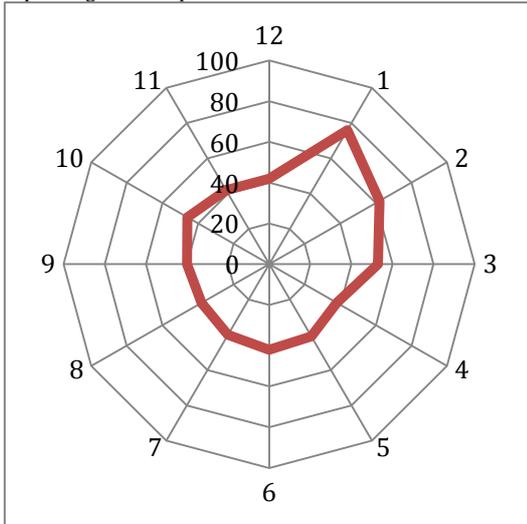
Cam Control 18
Alpha angles left hip



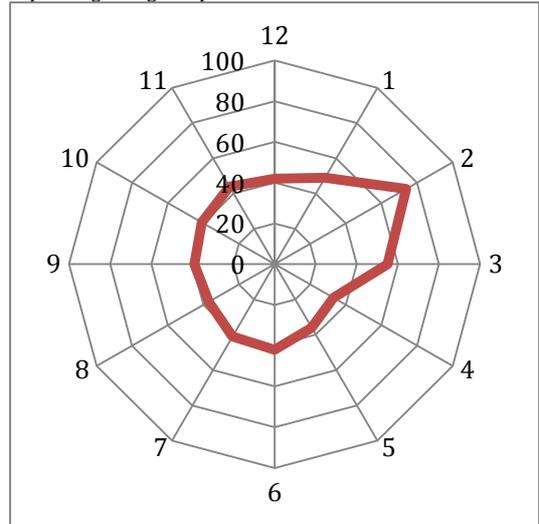
Alpha angles right hip



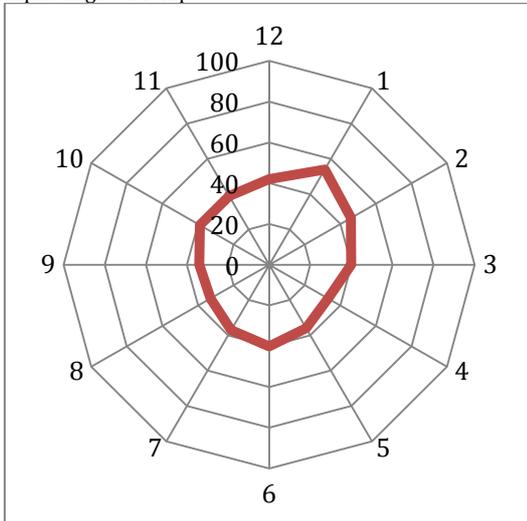
Cam Control 19
Alpha angles left hip



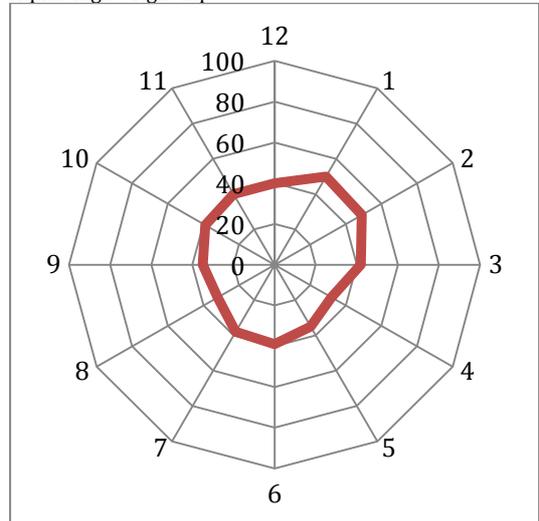
Alpha angles right hip



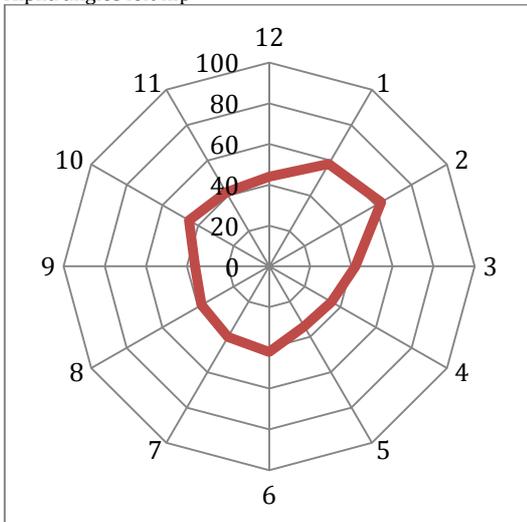
Cam Control 20
Alpha angles left hip



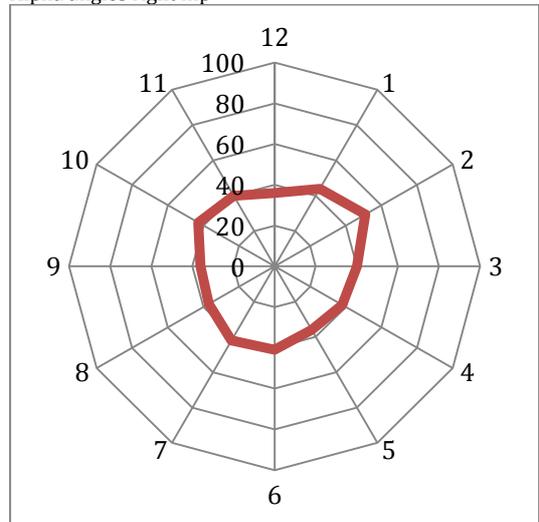
Alpha angles right hip



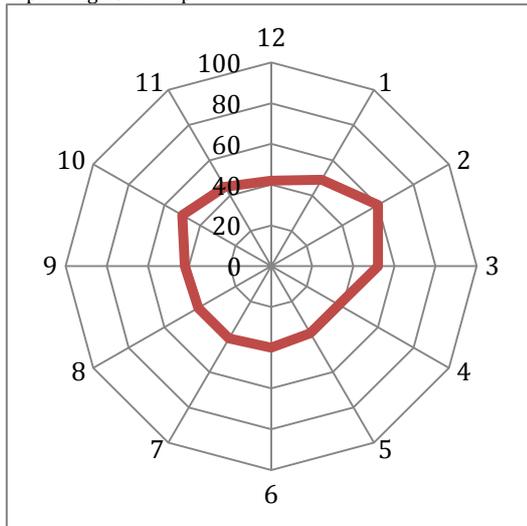
Cam Control 21
Alpha angles left hip



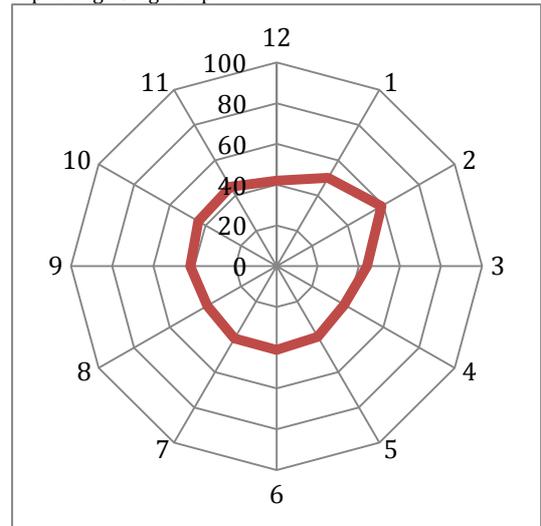
Alpha angles right hip



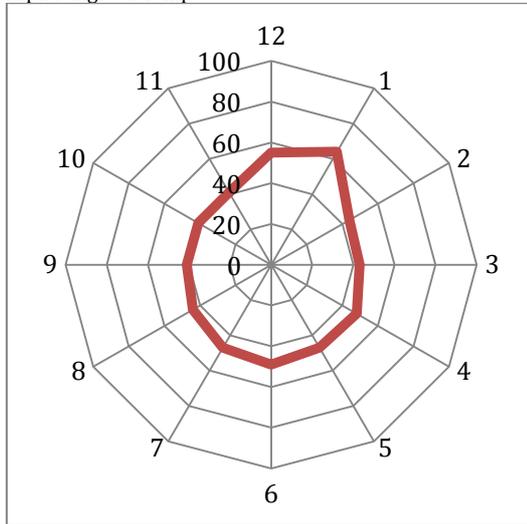
Cam Control 22
Alpha angles left hip



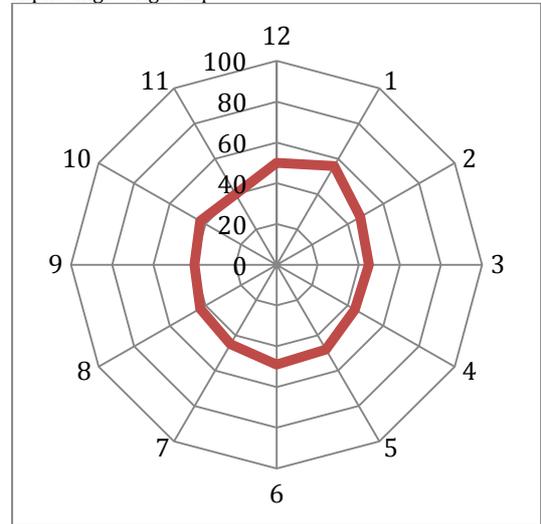
Alpha angles right hip



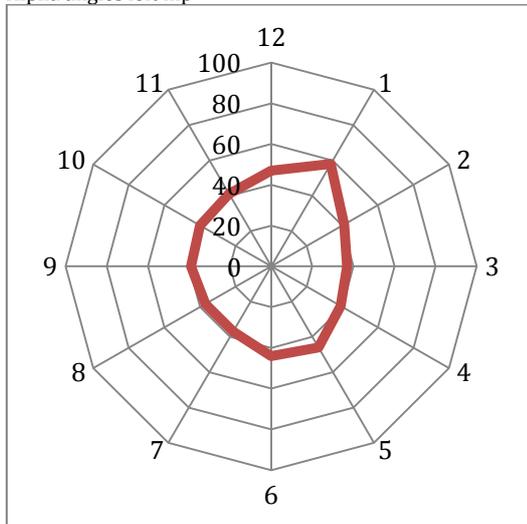
Cam Control 23
Alpha angles left hip



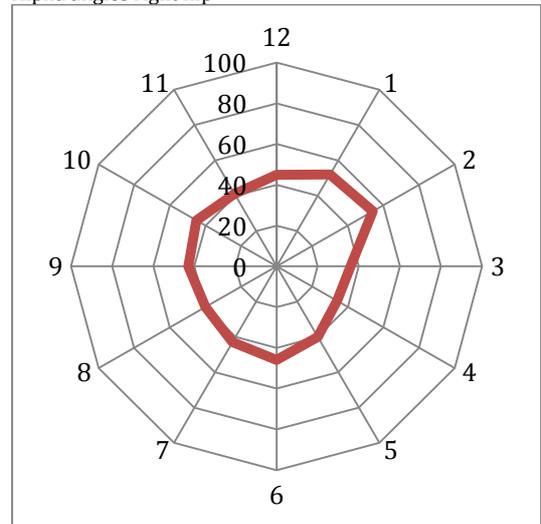
Alpha angles right hip



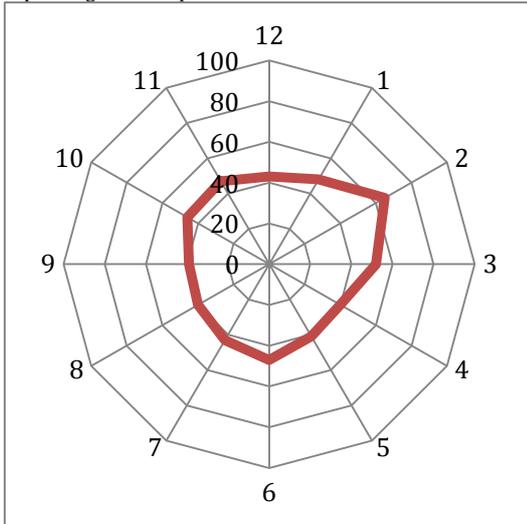
Cam Control 24
Alpha angles left hip



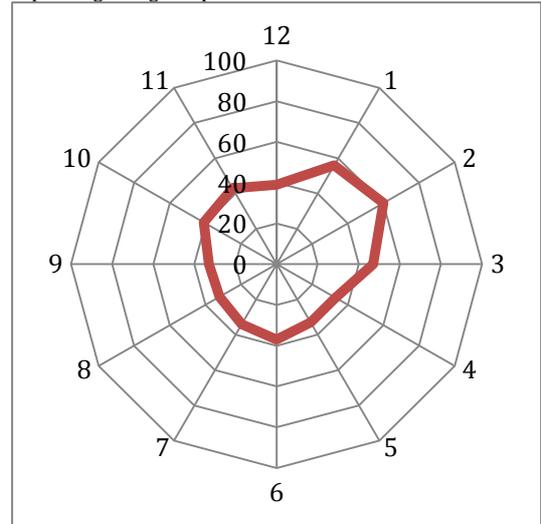
Alpha angles right hip



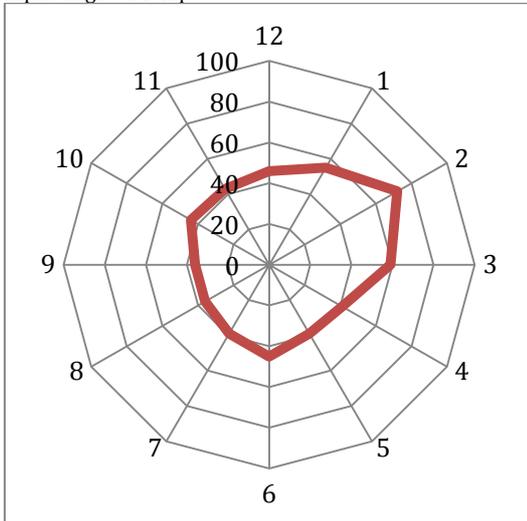
Cam Control 25
Alpha angles left hip



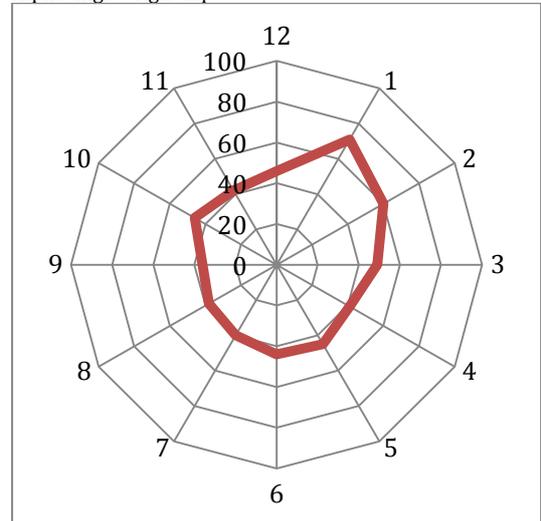
Alpha angles right hip



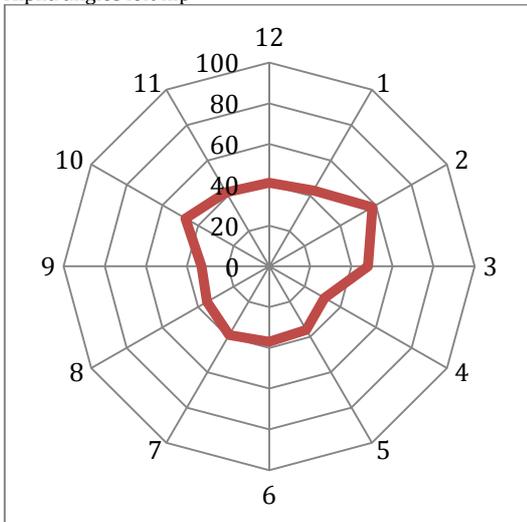
Cam Control 26
Alpha angles left hip



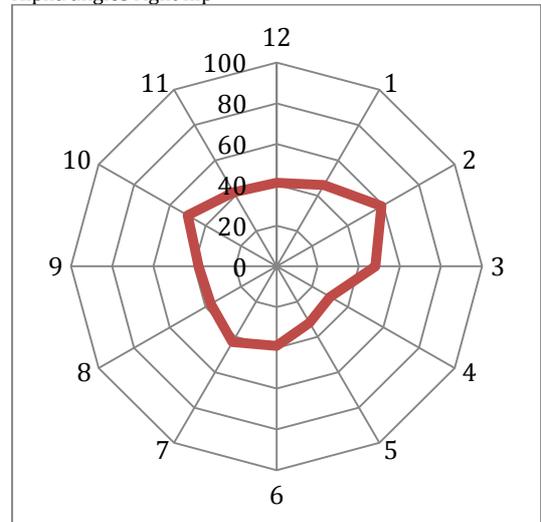
Alpha angles right hip



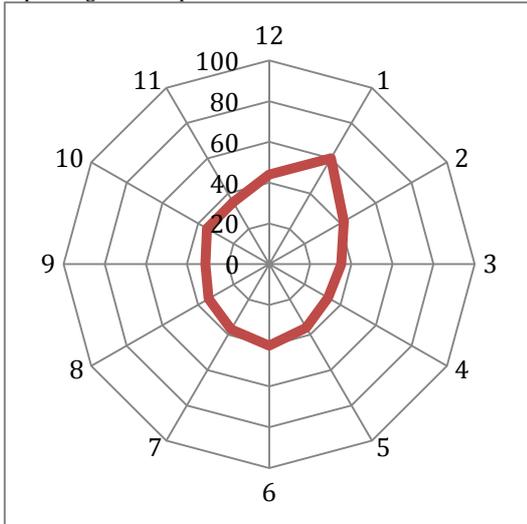
Cam Control 27
Alpha angles left hip



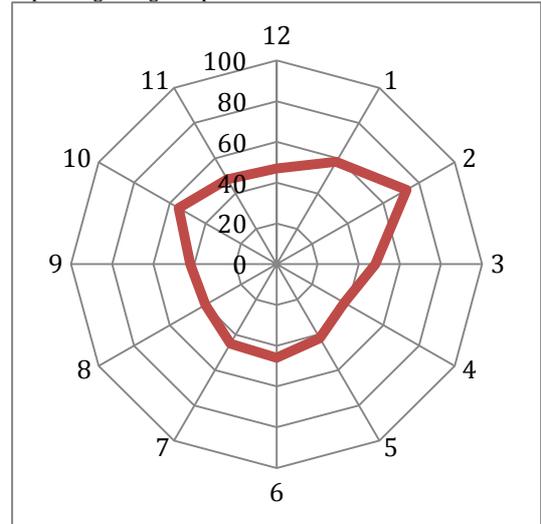
Alpha angles right hip



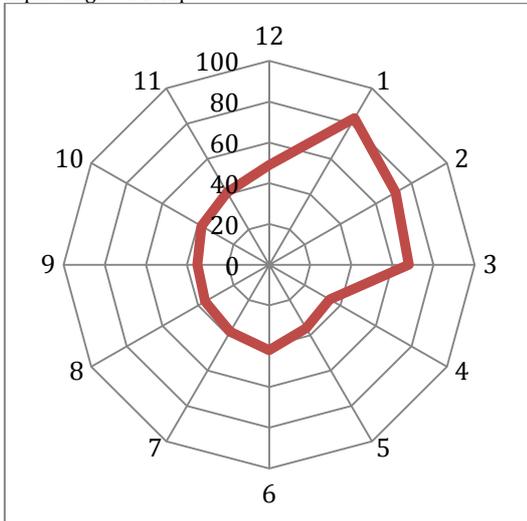
Cam Control 28
Alpha angles left hip



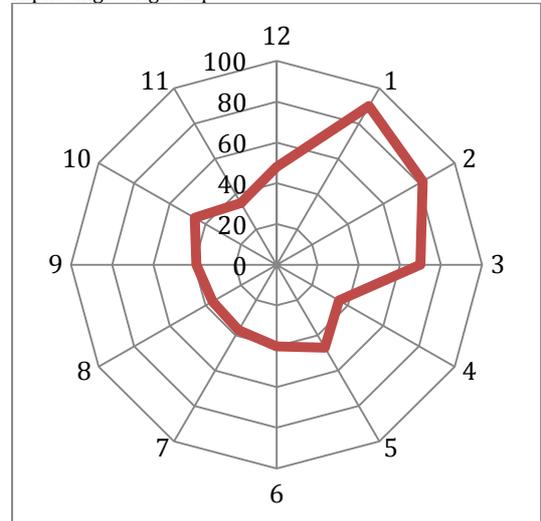
Alpha angles right hip



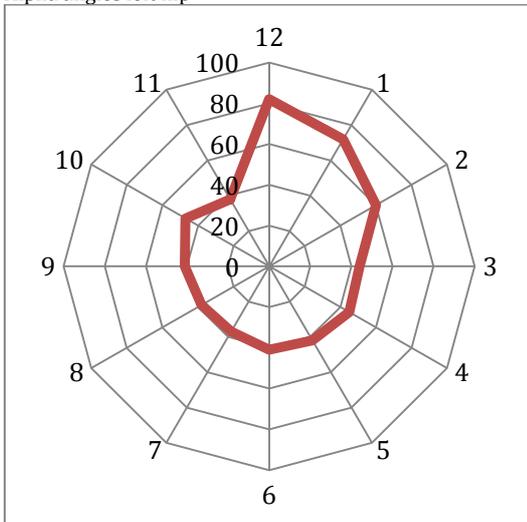
Control 29
Alpha angles left hip



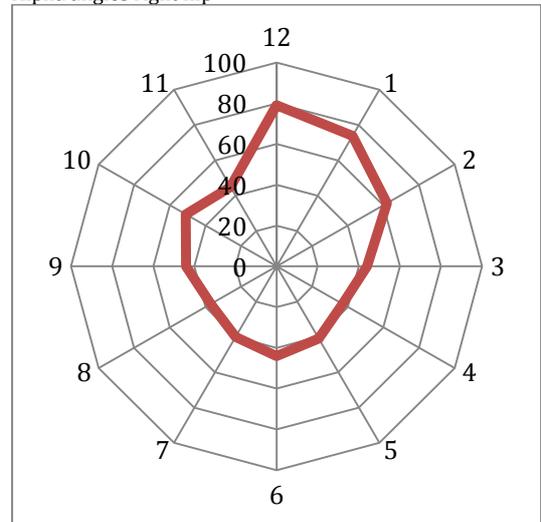
Alpha angles right hip



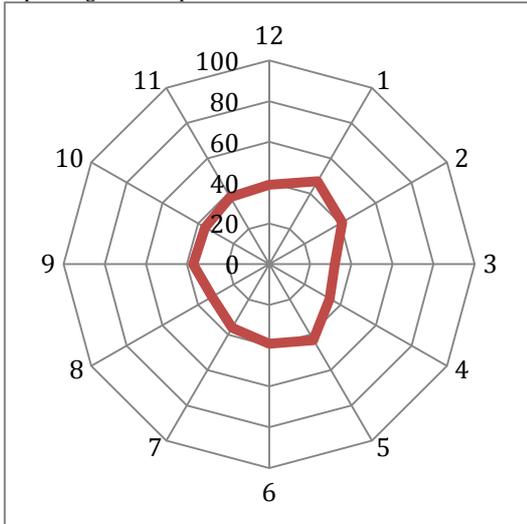
Cam Control 30
Alpha angles left hip



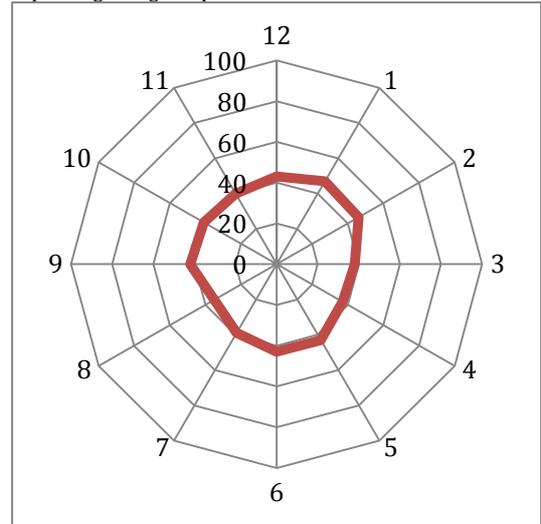
Alpha angles right hip



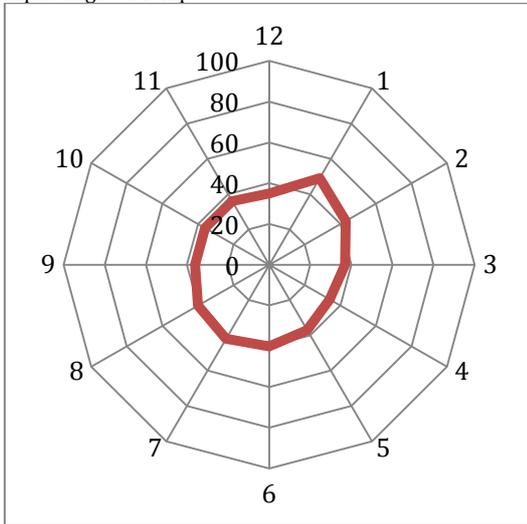
Cam Control 31
Alpha angles left hip



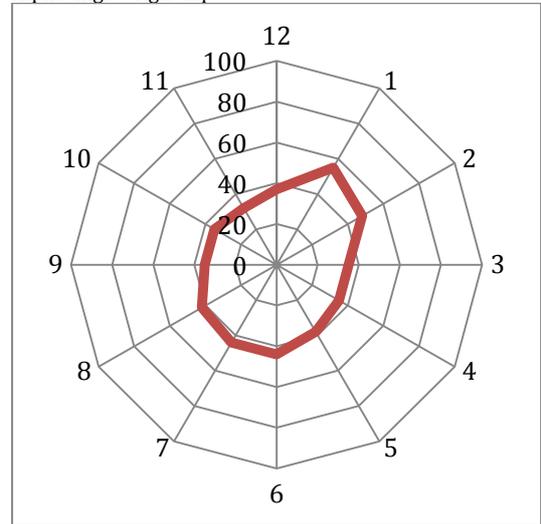
Alpha angles right hip



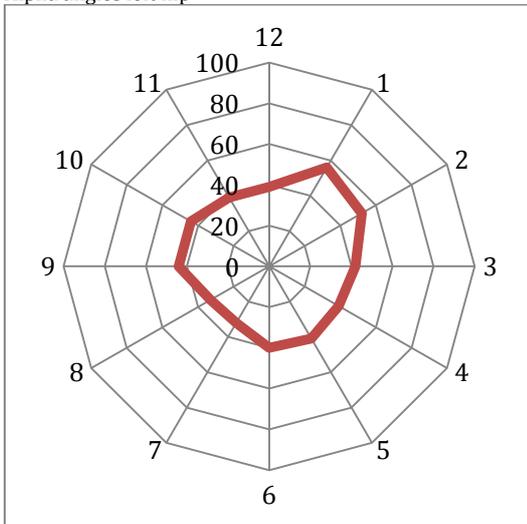
Cam Control 32
Alpha angles left hip



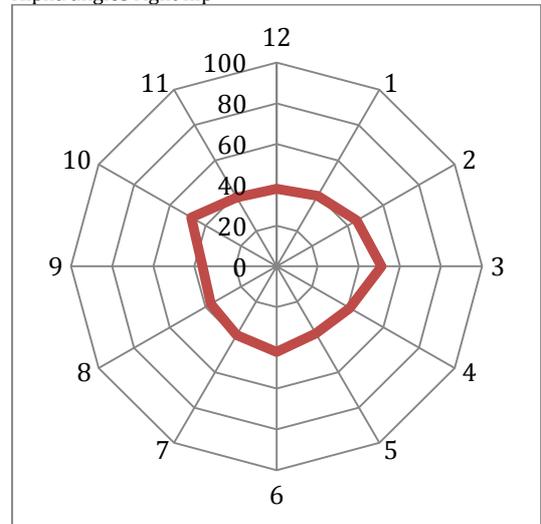
Alpha angles right hip



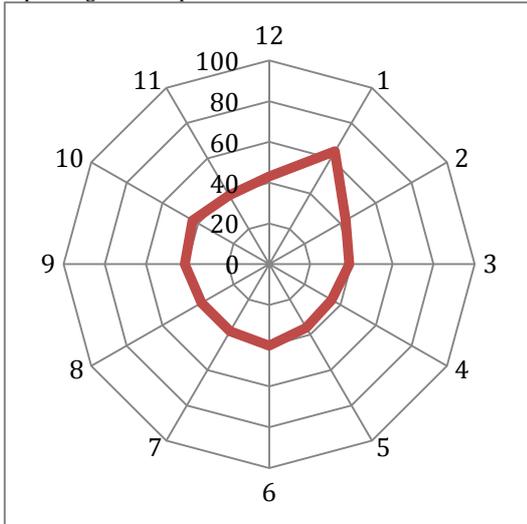
Cam Control 33
Alpha angles left hip



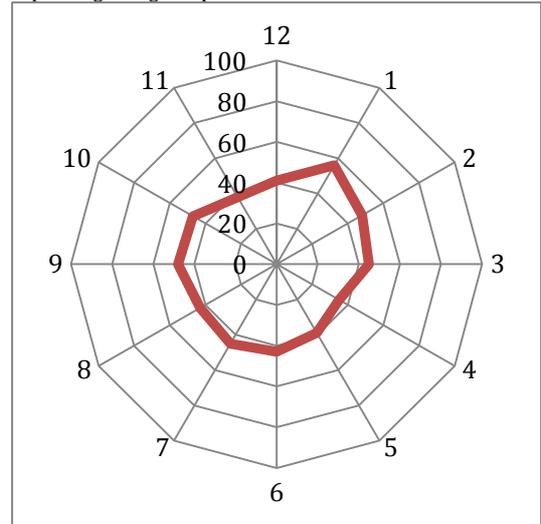
Alpha angles right hip



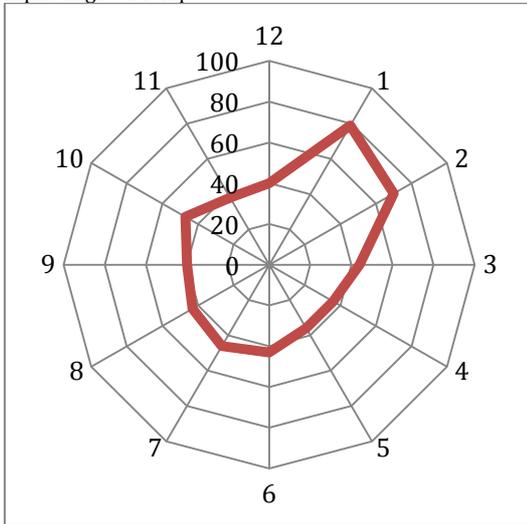
Cam Control 34
Alpha angles left hip



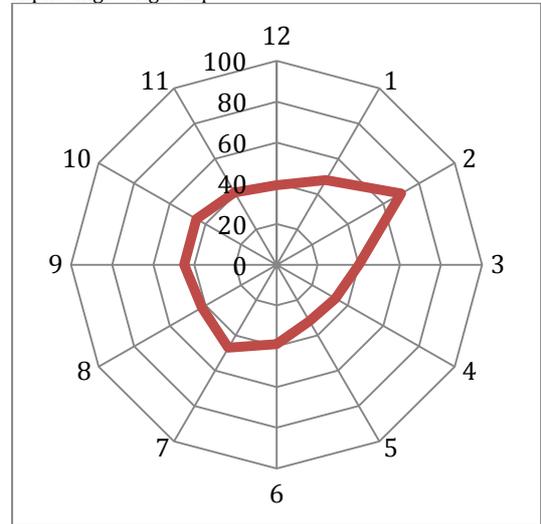
Alpha angles right hip



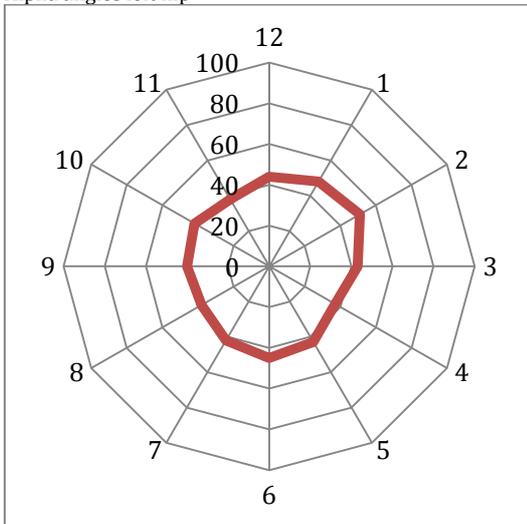
Cam Control 35
Alpha angles left hip



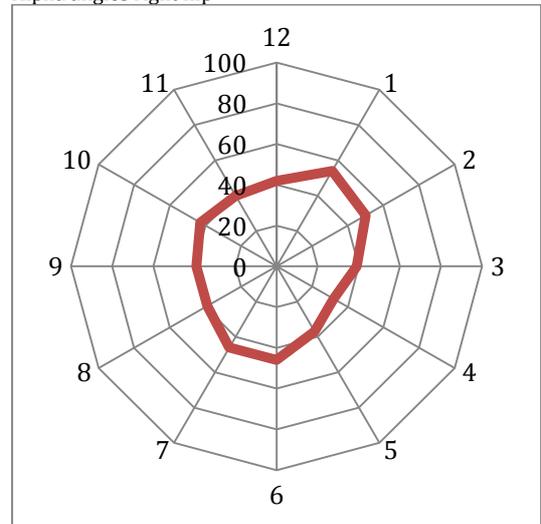
Alpha angles right hip



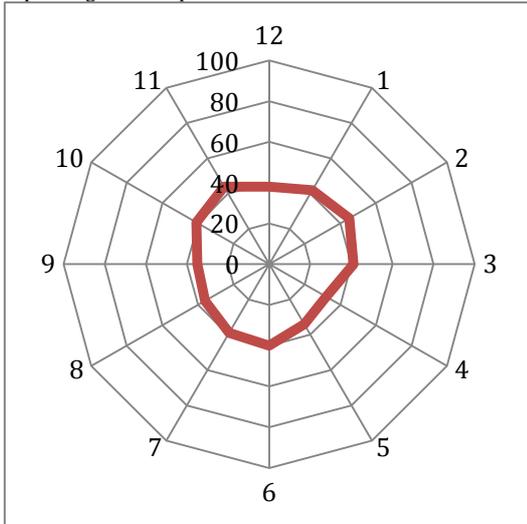
Cam Control 36
Alpha angles left hip



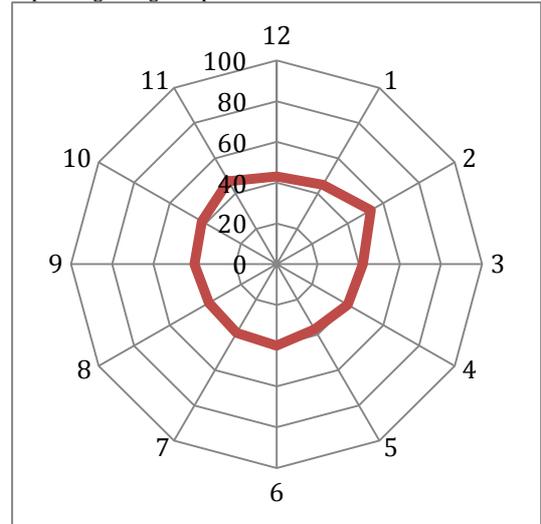
Alpha angles right hip



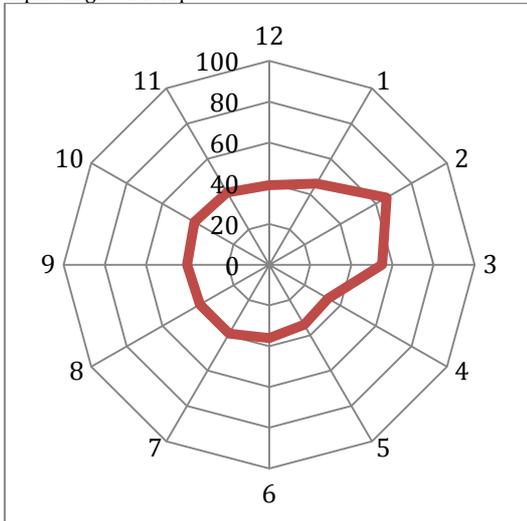
Cam Control 37
Alpha angles left hip



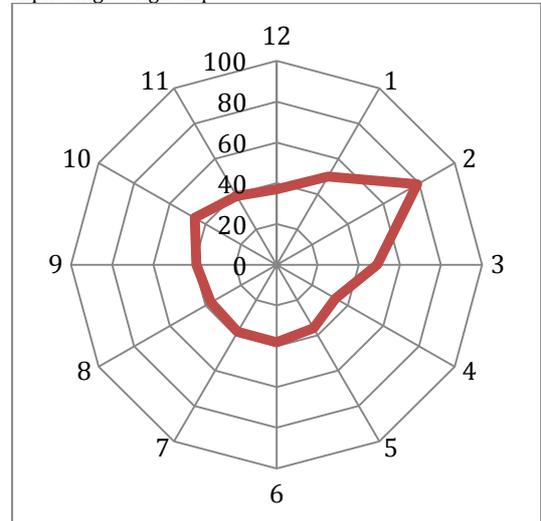
Alpha angles right hip



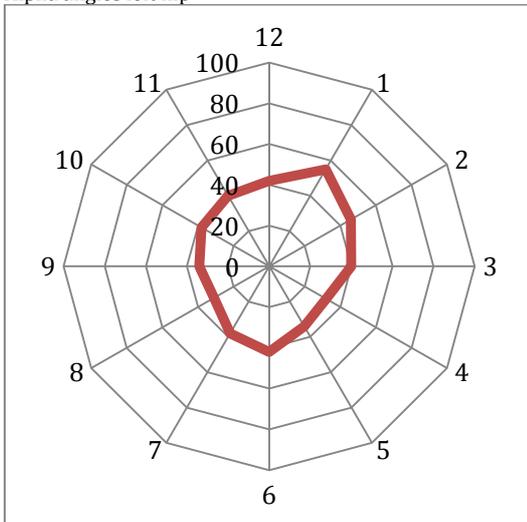
Cam Control 38
Alpha angles left hip



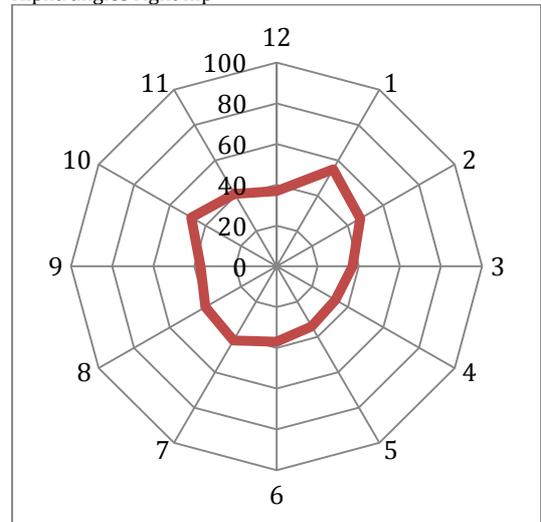
Alpha angles right hip



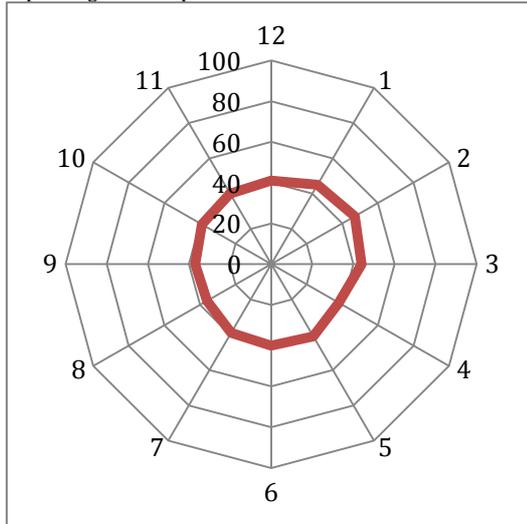
Cam Control 39
Alpha angles left hip



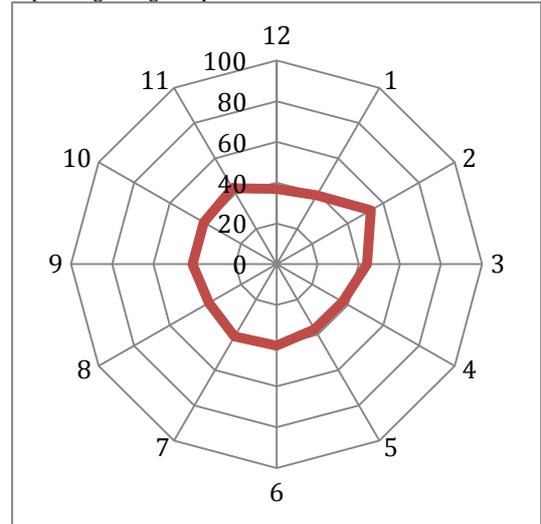
Alpha angles right hip



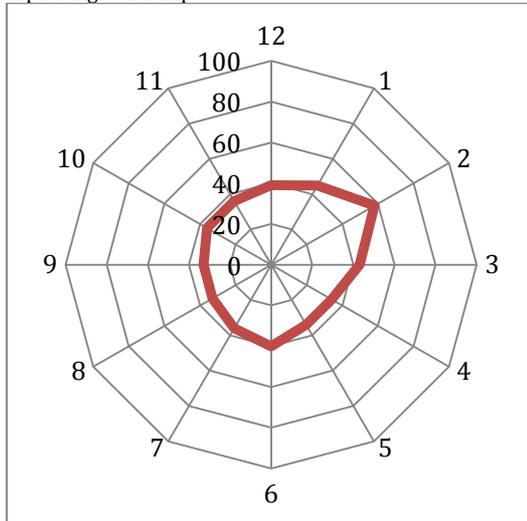
Cam Control 40
Alpha angles left hip



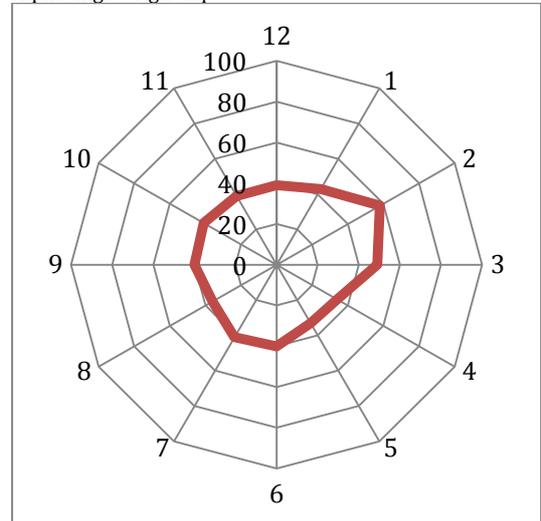
Alpha angles right hip



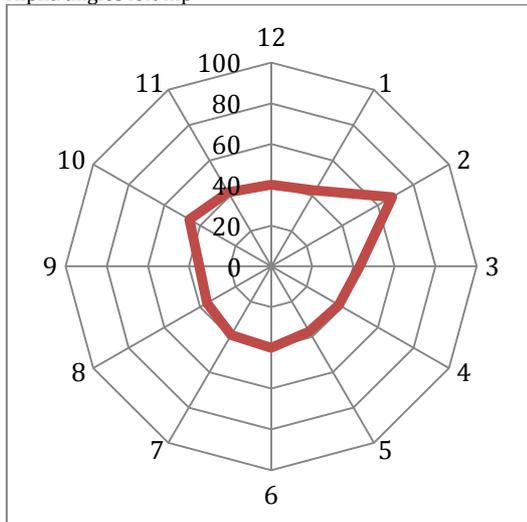
Cam Control 41
Alpha angles left hip



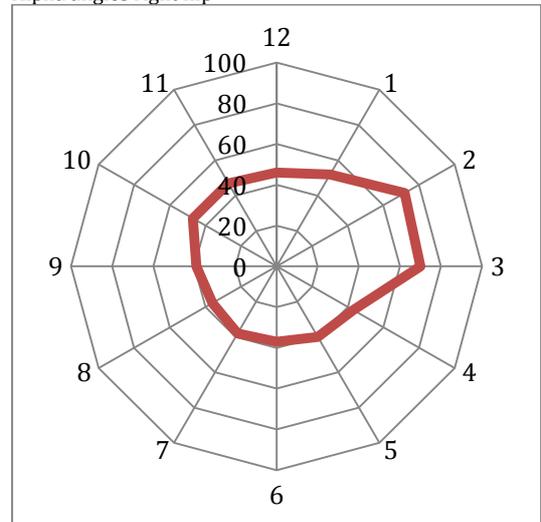
Alpha angles right hip



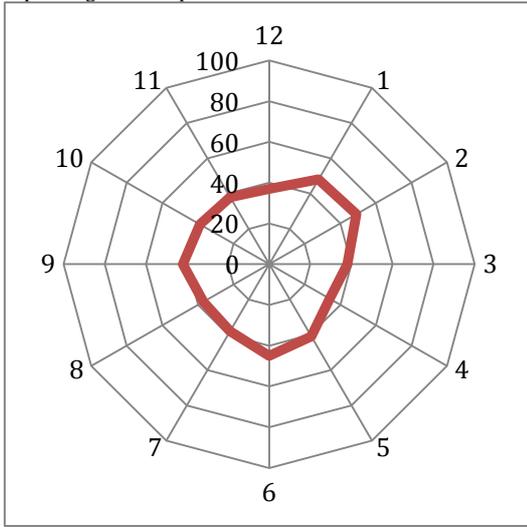
Cam Control 42
Alpha angles left hip



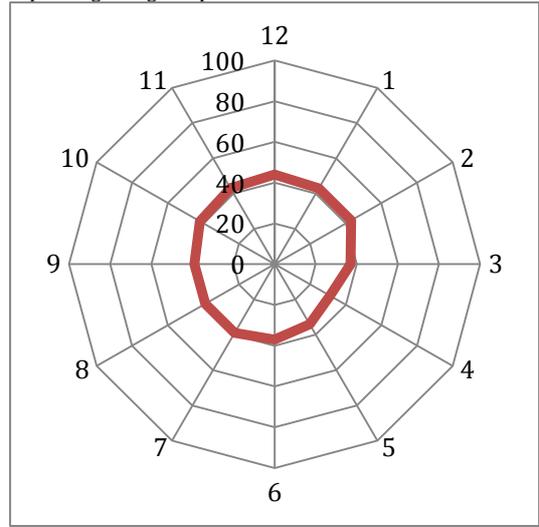
Alpha angles right hip



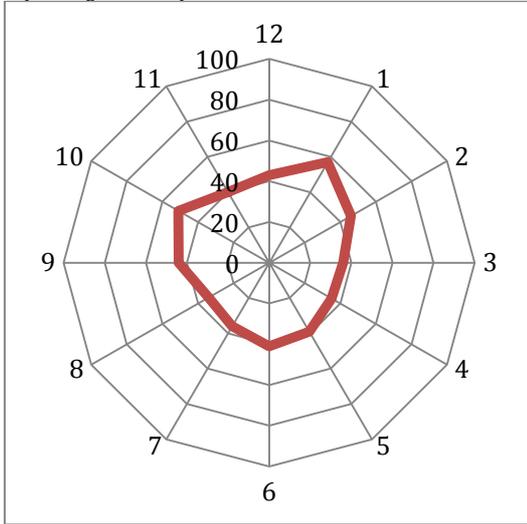
Cam Control 43
Alpha angles left hip



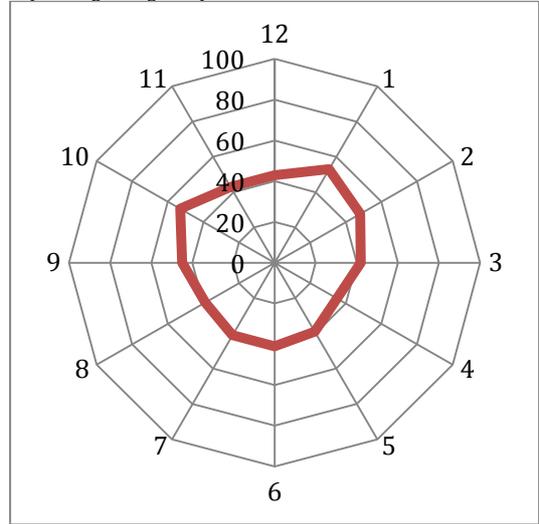
Alpha angles right hip



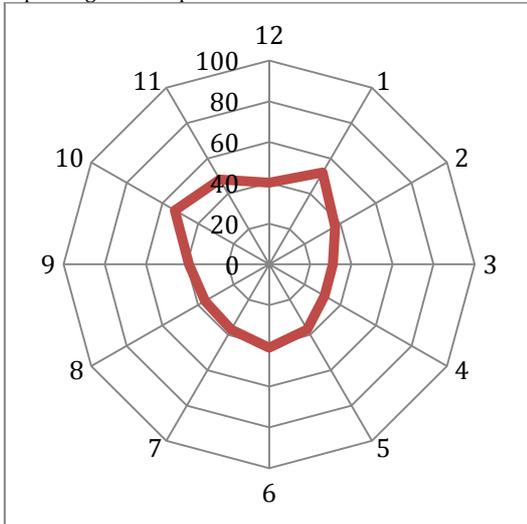
Cam Control 44
Alpha angles left hip



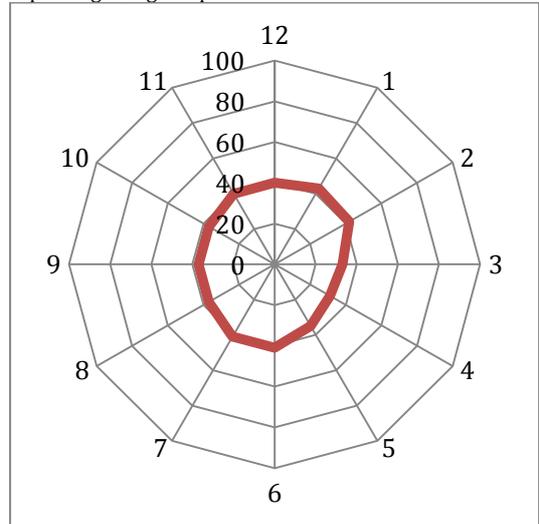
Alpha angles right hip



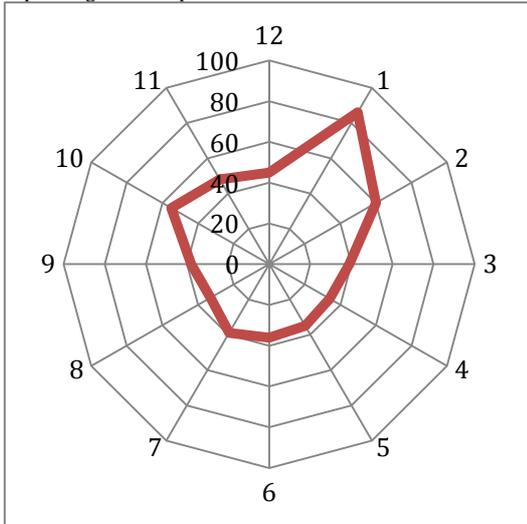
Cam Control 45
Alpha angles left hip



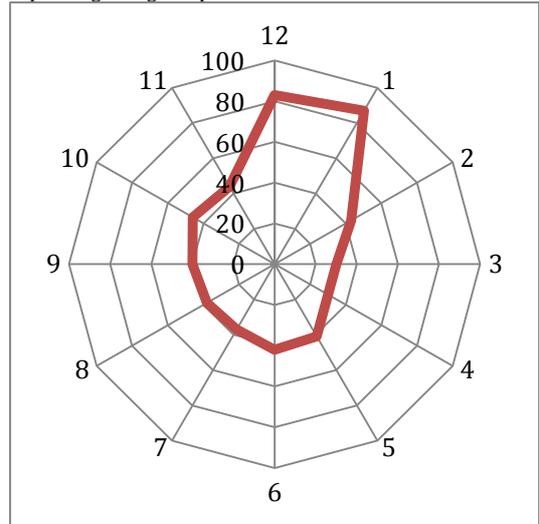
Alpha angles right hip



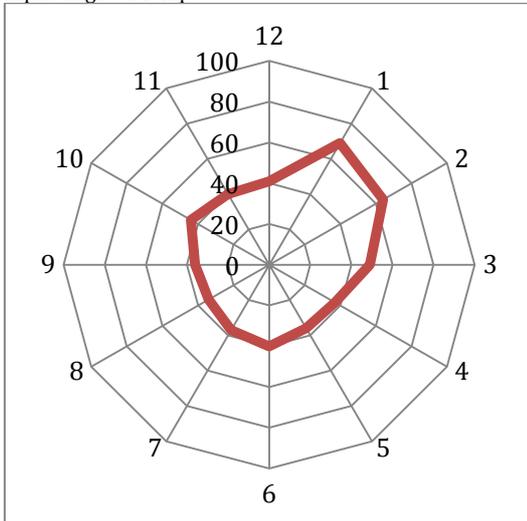
Cam Control 46
Alpha angles left hip



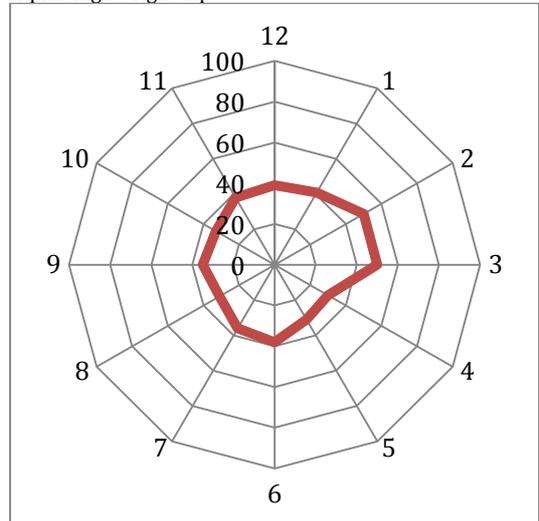
Alpha angles right hip



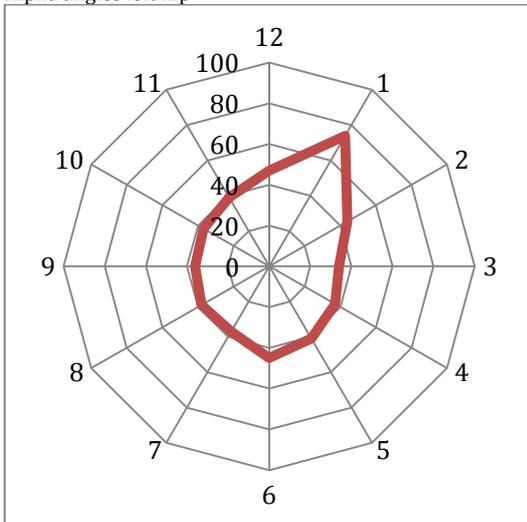
Cam Control 47
Alpha angles left hip



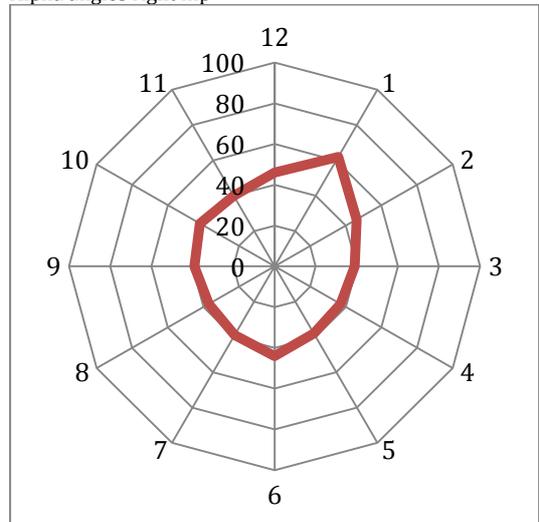
Alpha angles right hip



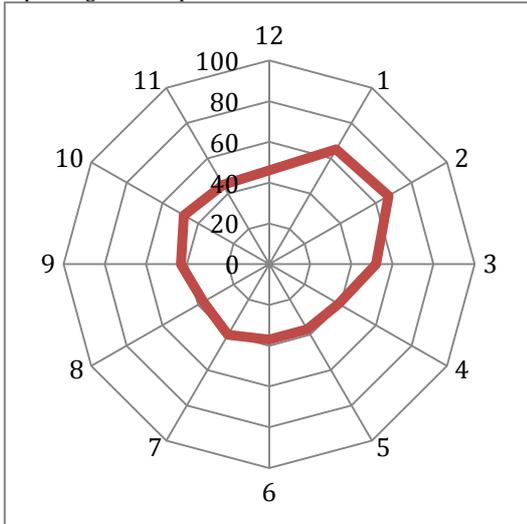
Cam Control 48
Alpha angles left hip



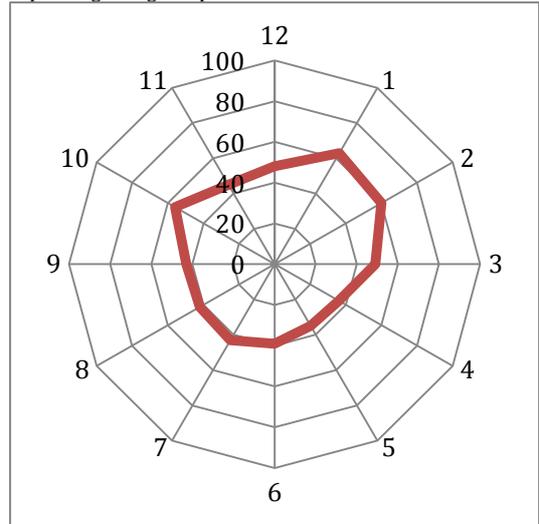
Alpha angles right hip



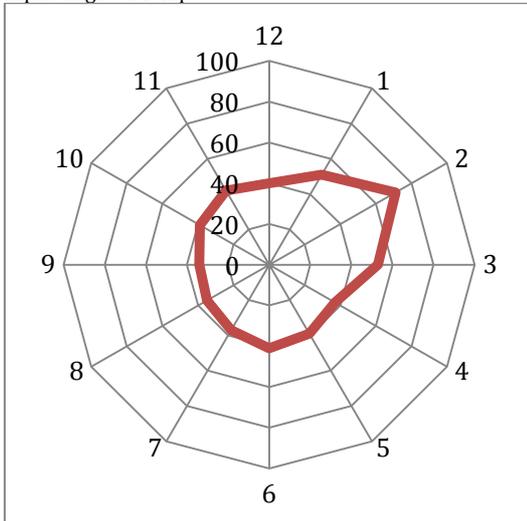
Cam Control 49
Alpha angles left hip



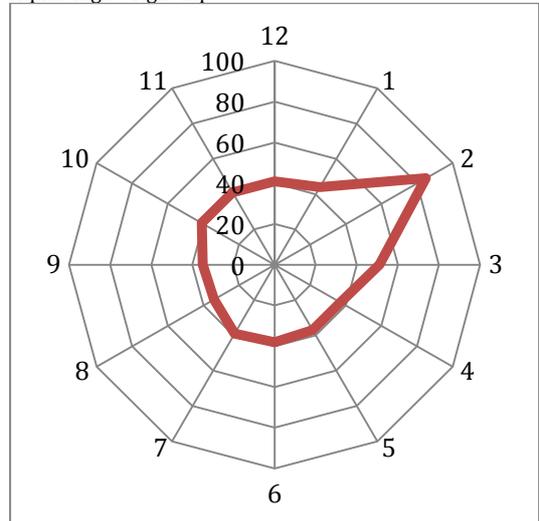
Alpha angles right hip



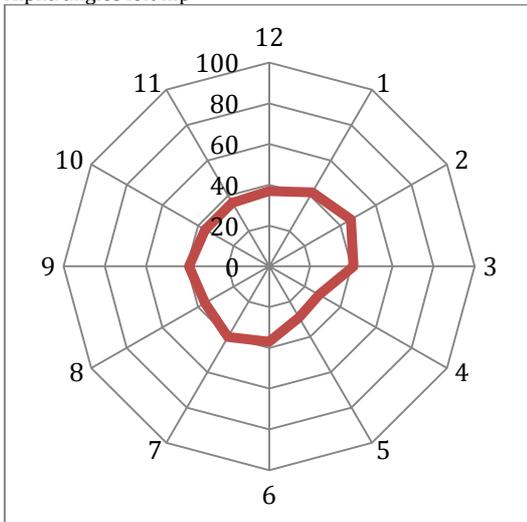
Cam Control 50
Alpha angles left hip



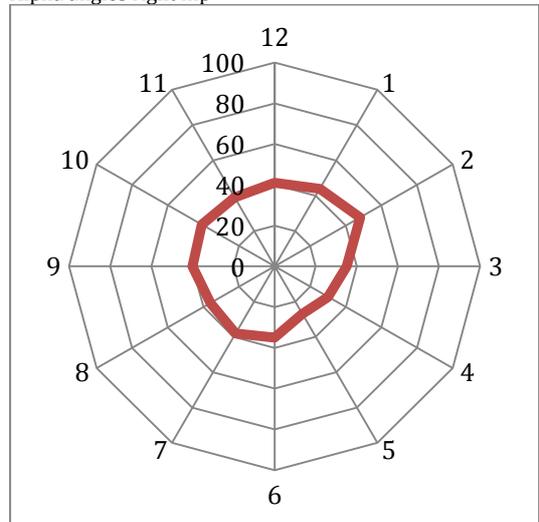
Alpha angles right hip



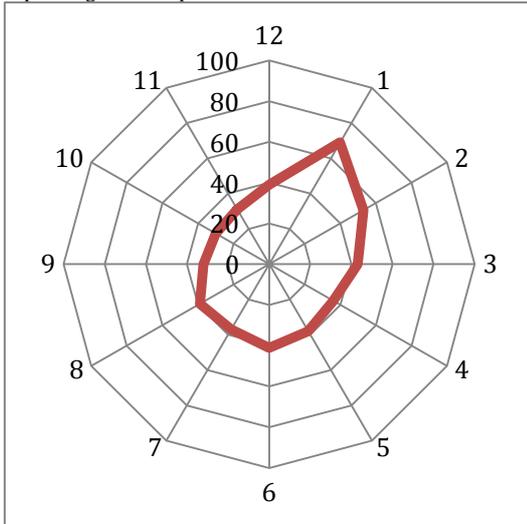
Cam Control 51
Alpha angles left hip



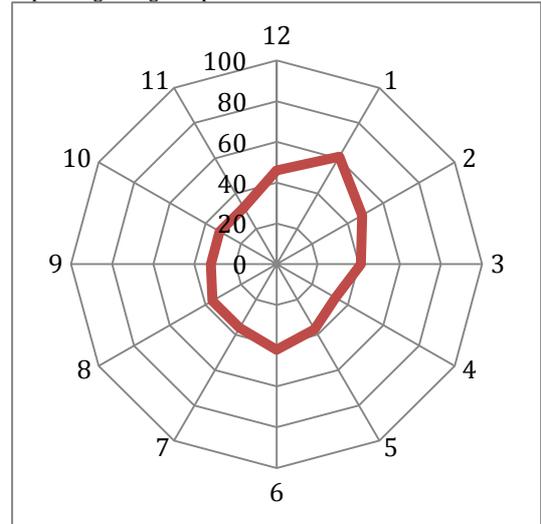
Alpha angles right hip



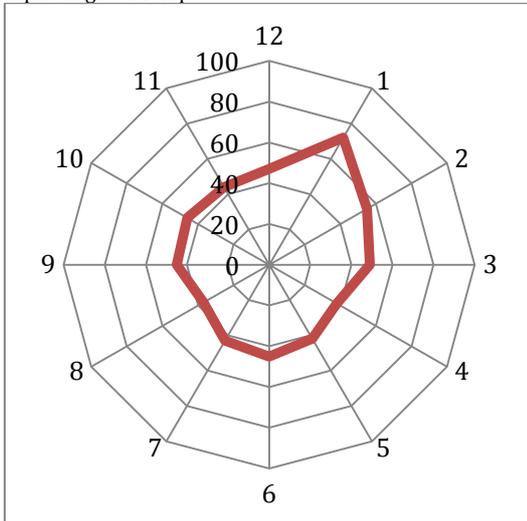
Cam Control 52
Alpha angles left hip



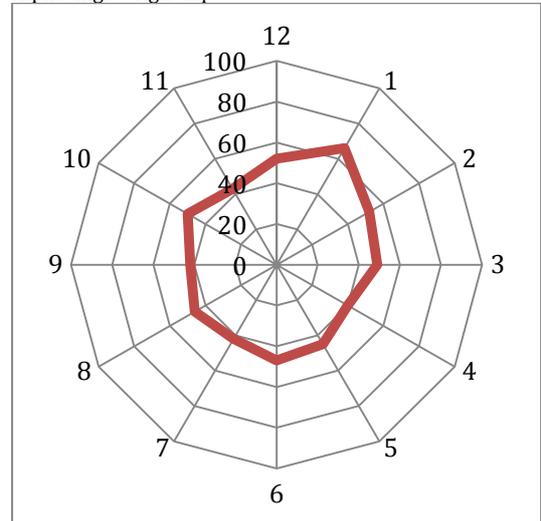
Alpha angles right hip



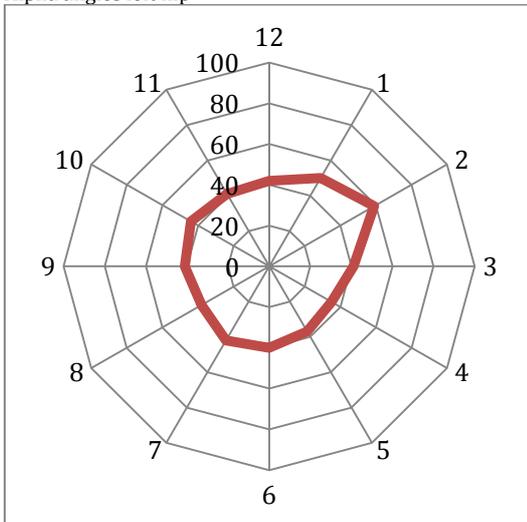
Cam Control 53
Alpha angles left hip



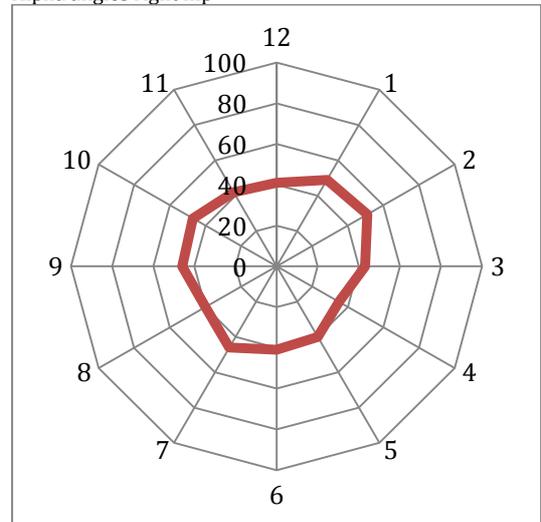
Alpha angles right hip



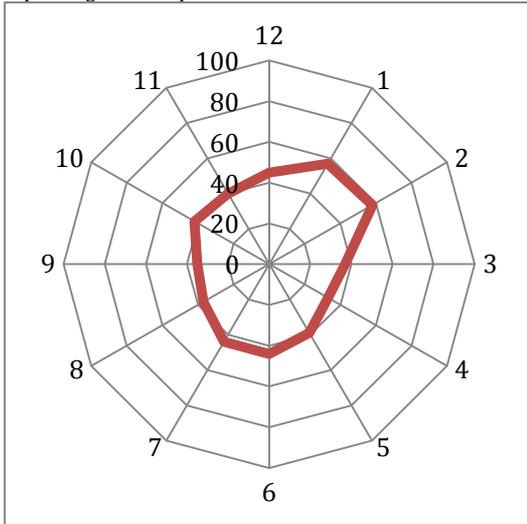
Cam Control 54
Alpha angles left hip



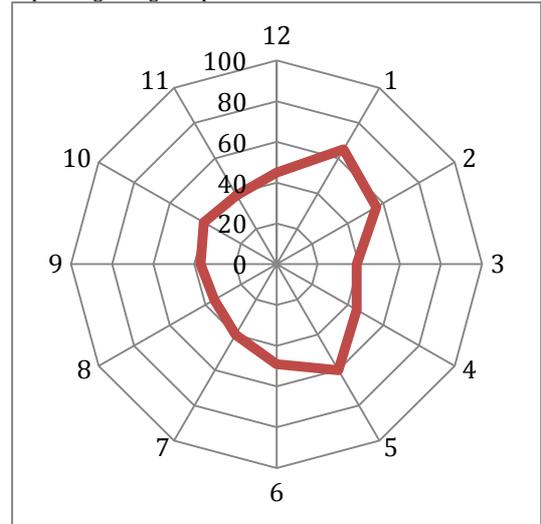
Alpha angles right hip



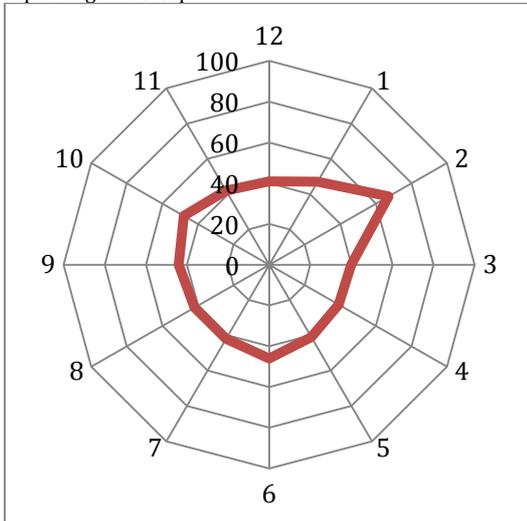
Cam Control 55
Alpha angles left hip



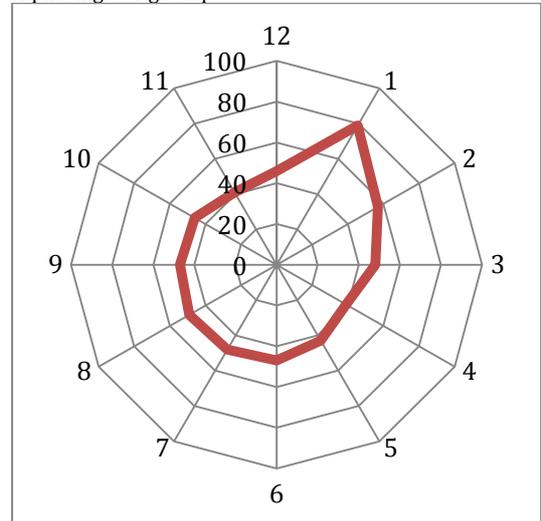
Alpha angles right hip



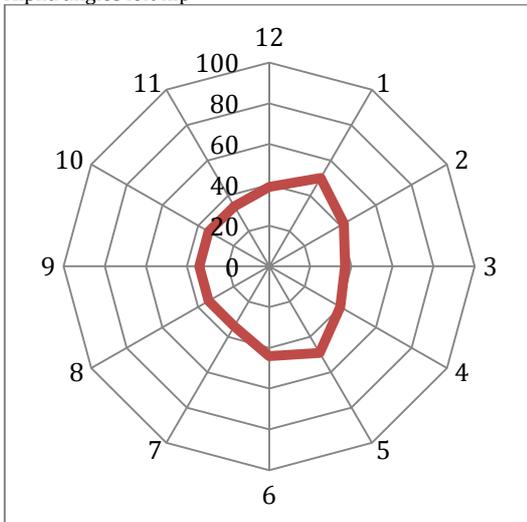
Cam Control 56
Alpha angles left hip



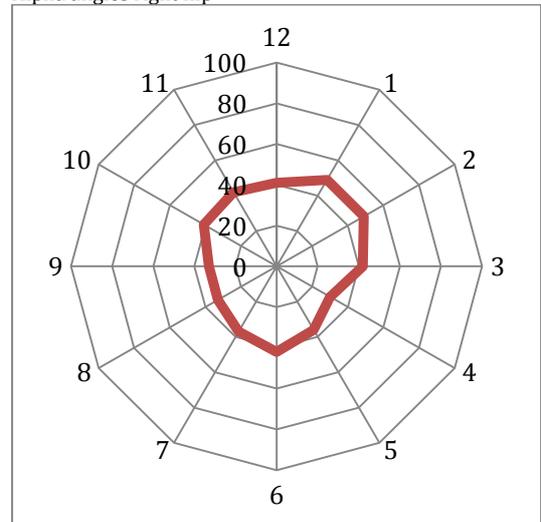
Alpha angles right hip



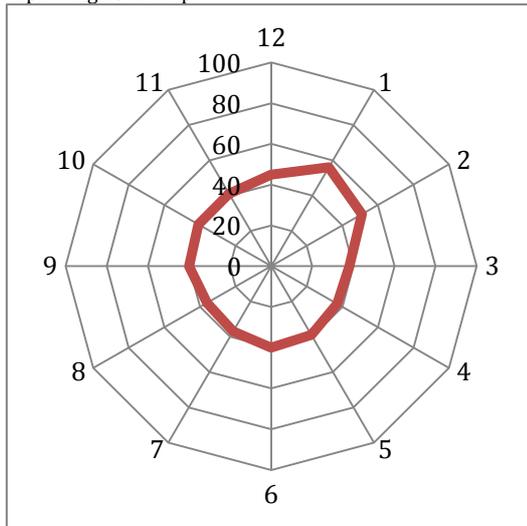
Cam Control 57
Alpha angles left hip



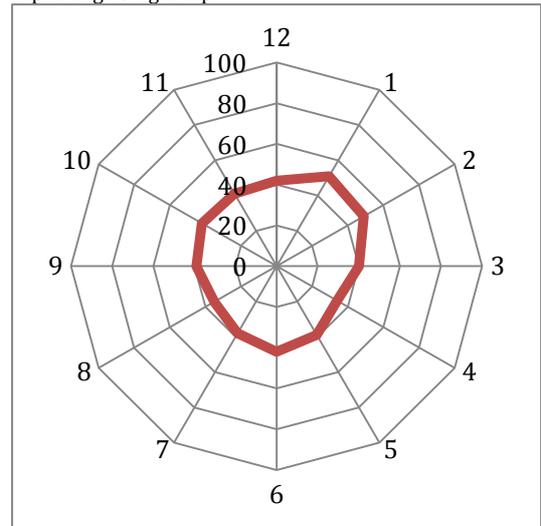
Alpha angles right hip



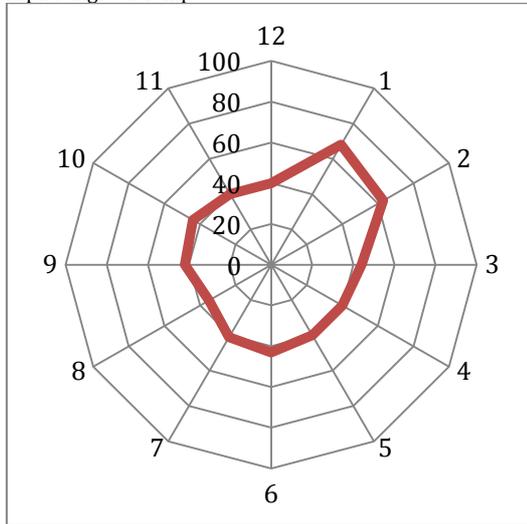
Cam Control 58
Alpha angles left hip



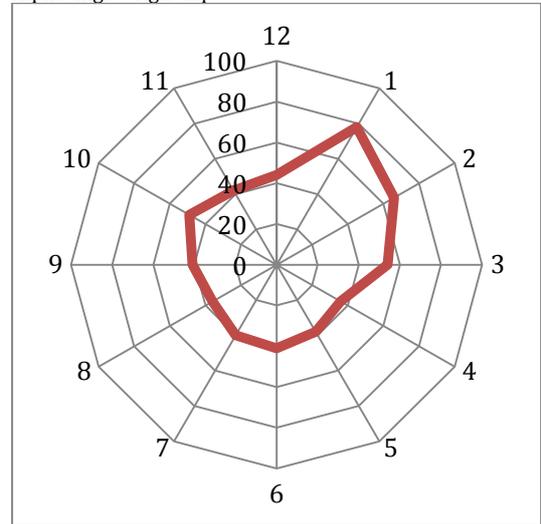
Alpha angles right hip



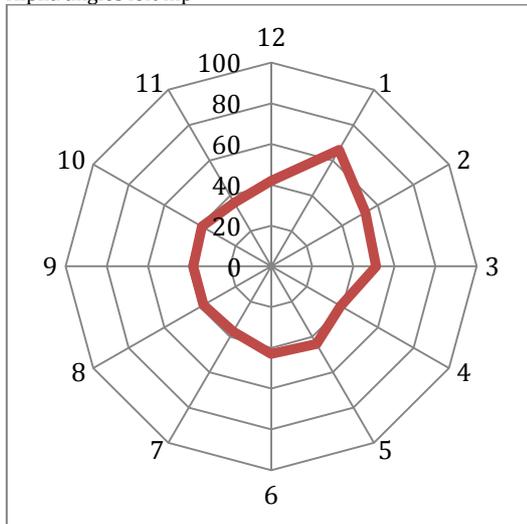
Cam Control 59
Alpha angles left hip



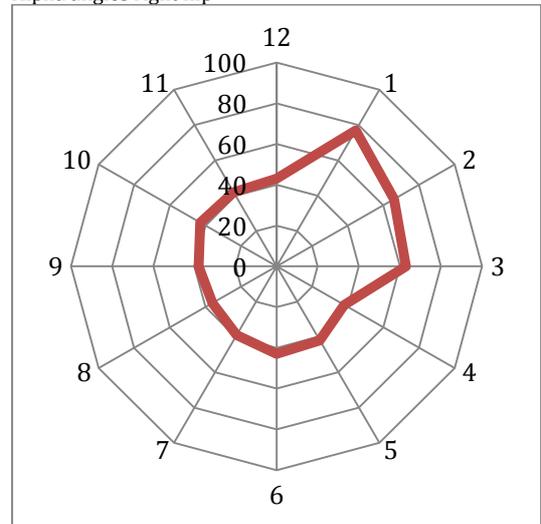
Alpha angles right hip



Cam Control 60
Alpha angles left hip



Alpha angles right hip



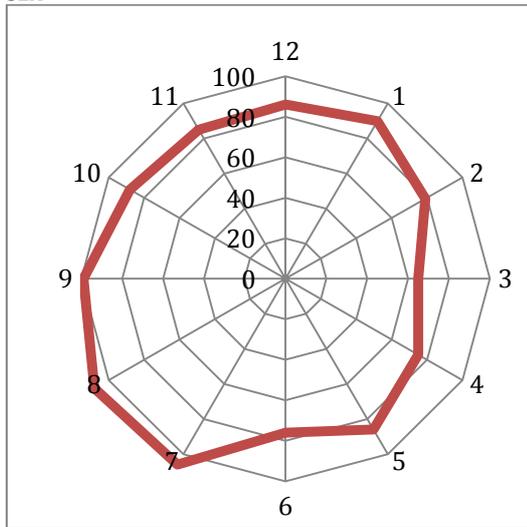
11.2.4 Chapter 4; Coordinates of the ROC curve for SEA to determine the presence of pincer morphology

Coordinates of the Curve			
Test Result Variable(s)	Positive if Greater Than or Equal To ^a	Sensitivity	1 - Specificity
SEA 12 o'clock	60.0000	1.000	1.000
	61.5000	1.000	.983
	63.0000	1.000	.948
	65.5000	1.000	.931
	68.0000	1.000	.879
	69.5000	.966	.845
	70.5000	.966	.828
	71.5000	.966	.793
	72.5000	.966	.724
	73.5000	.862	.707
	74.5000	.793	.690
	75.5000	.724	.638
	76.5000	.724	.552
	77.5000	.655	.517
	78.5000	.621	.466
	79.5000	.517	.379
	80.5000	.483	.293
	81.5000	.448	.259
	82.5000	.414	.259
	83.5000	.414	.224
	84.5000	.310	.207
	85.5000	.276	.207
	86.5000	.241	.155
	87.5000	.241	.138
88.5000	.207	.138	
89.5000	.207	.121	
90.5000	.103	.086	
91.5000	.103	.034	
92.5000	.069	.017	
95.0000	.069	.000	
100.0000	.034	.000	
104.0000	.000	.000	
SEA 2 o'clock	59.0000	1.000	1.000
	61.5000	1.000	.983
	64.0000	1.000	.948
	66.0000	1.000	.931
	67.5000	1.000	.914
	68.5000	1.000	.879
	69.5000	1.000	.845
	70.5000	.966	.845
	71.5000	.966	.810
	72.5000	.966	.759
	73.5000	.897	.724
	74.5000	.897	.707
	75.5000	.862	.621
	76.5000	.862	.603
	77.5000	.862	.552
	78.5000	.862	.517
	79.5000	.793	.431
	80.5000	.759	.379
	81.5000	.655	.345
	82.5000	.552	.310
	84.0000	.448	.276
	85.5000	.379	.241
	86.5000	.345	.241
	87.5000	.241	.224
88.5000	.241	.190	
89.5000	.172	.172	
90.5000	.103	.155	
91.5000	.103	.138	
92.5000	.069	.086	

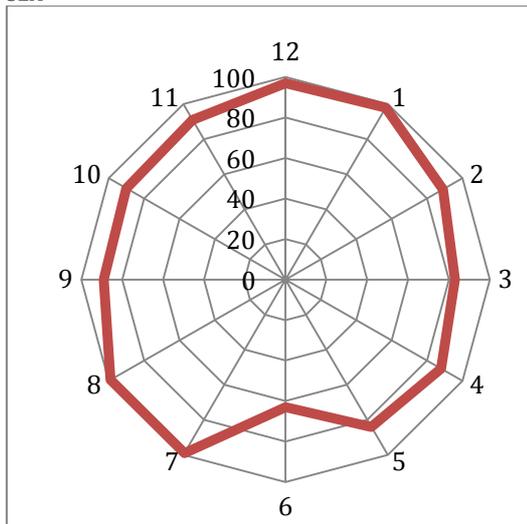
	93.5000	.034	.034
	95.0000	.034	.017
	97.5000	.034	.000
	100.0000	.000	.000
mean SEA 12-3 o'clock	61.3000	1.000	1.000
	63.0500	1.000	.983
	64.4000	1.000	.966
	65.4000	1.000	.948
	66.0500	1.000	.931
	66.5500	1.000	.914
	67.6500	1.000	.897
	69.0000	1.000	.879
	70.1500	1.000	.845
	71.1500	1.000	.828
	71.7500	.966	.828
	72.4000	.966	.810
	72.9000	.931	.776
	73.4000	.931	.759
	73.9000	.931	.741
	74.1500	.931	.724
	74.4000	.931	.707
	74.7500	.897	.707
	75.2500	.897	.638
	75.6500	.897	.603
	75.9000	.897	.586
	76.1500	.897	.569
	76.4000	.897	.517
	76.6500	.897	.500
	76.9000	.828	.500
	77.1500	.793	.466
	77.6500	.759	.466
	78.1500	.724	.448
	78.4000	.724	.431
	78.6500	.690	.431
	78.9000	.655	.431
	79.1500	.655	.397
	79.4000	.621	.379
	79.6500	.621	.362
	79.9000	.586	.345
	80.5000	.517	.345
	81.1500	.483	.345
	81.4000	.414	.328
	81.6500	.414	.276
	81.9000	.379	.259
82.5000	.345	.241	
83.1500	.310	.241	
83.4000	.310	.207	
84.2500	.276	.207	
85.1500	.276	.190	
85.9000	.241	.190	
87.0000	.241	.155	
87.9000	.207	.138	
88.4000	.172	.138	
88.6500	.138	.103	
89.3000	.103	.086	
89.9000	.103	.069	
90.9000	.103	.034	
93.4000	.034	.034	
96.6500	.034	.000	
99.3000	.000	.000	
The test result variable(s): SEA 12 o'clock, SEA 2 o'clock, mean SEA 12-3 o'clock has at least one tie between the positive actual state group and the negative actual state group.			
a. The smallest cutoff value is the minimum observed test value minus 1, and the largest cutoff value is the maximum observed test value plus 1. All the other cutoff values are the averages of two consecutive ordered observed test values.			

11.2.5 Chapter 4; Radar plots for pincer morphology cases

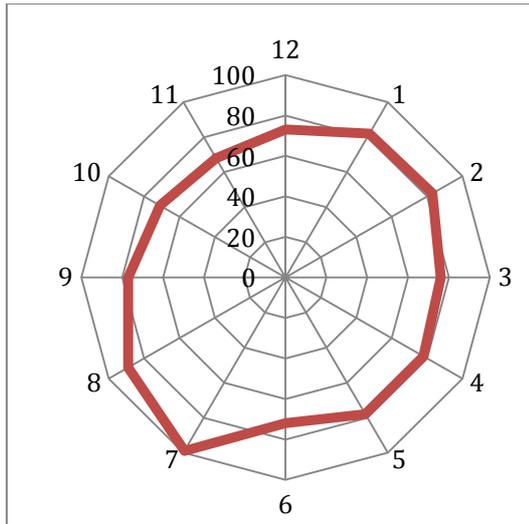
Pincer Case 1
SEA



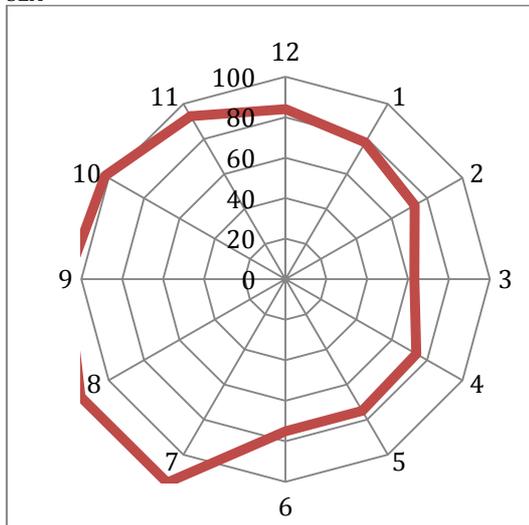
Pincer Case 2
SEA



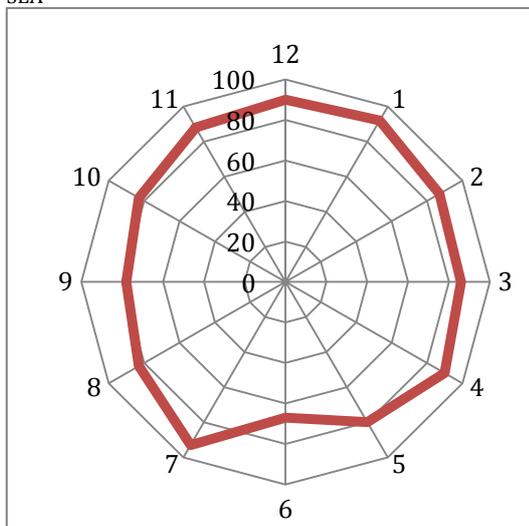
Pincer Case 3
SEA



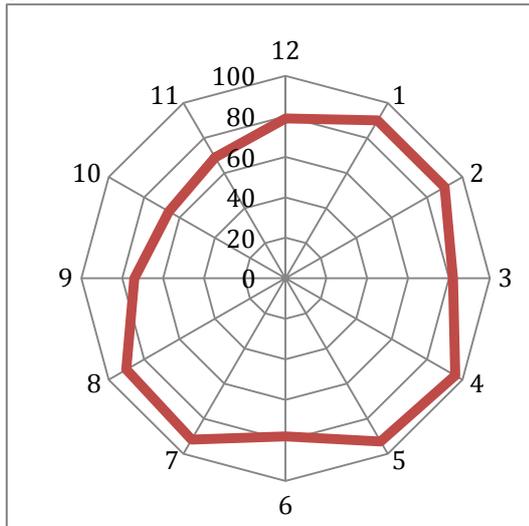
Pincer Case 4
SEA



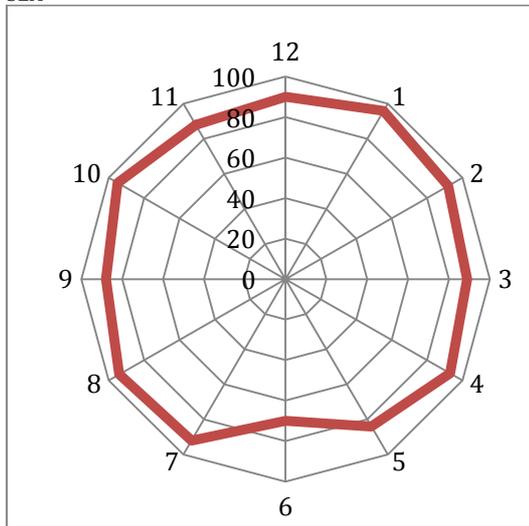
Pincer Case 5
SEA



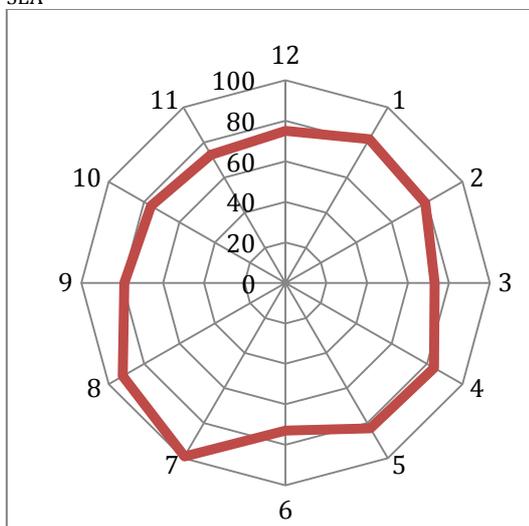
Pincer Case 6
SEA



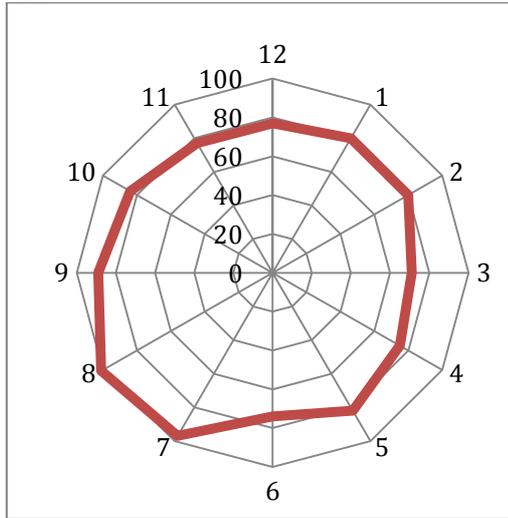
Pincer Case 7
SEA



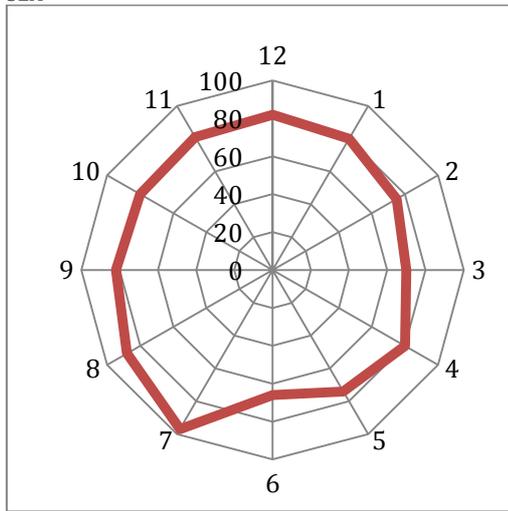
Pincer Case 8
SEA



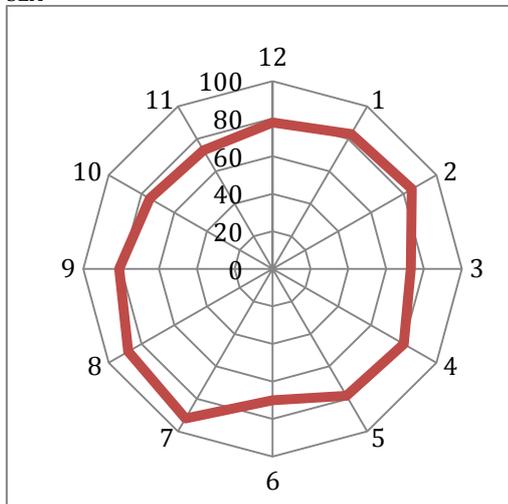
Pincer Case 9
SEA



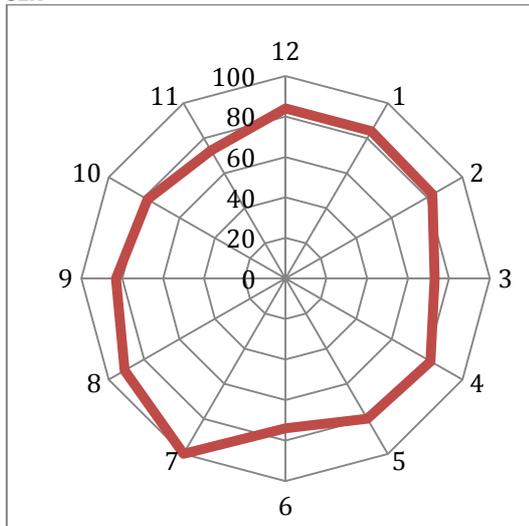
Pincer Case 10
SEA



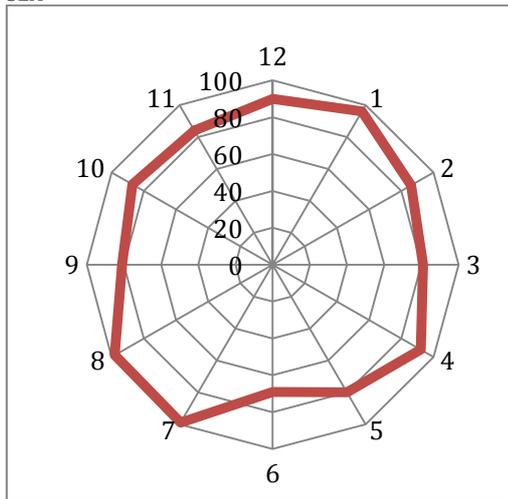
Pincer Case 11
SEA



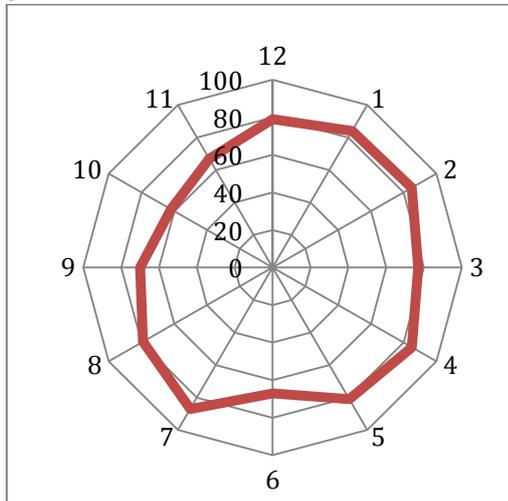
Pincer Case 12
SEA



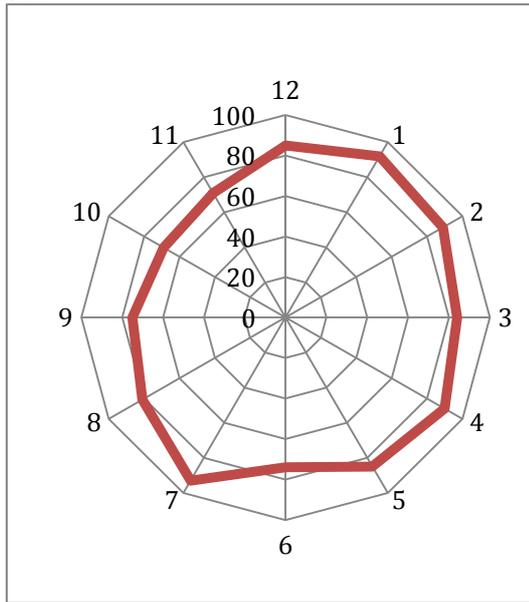
Pincer Case 13
SEA



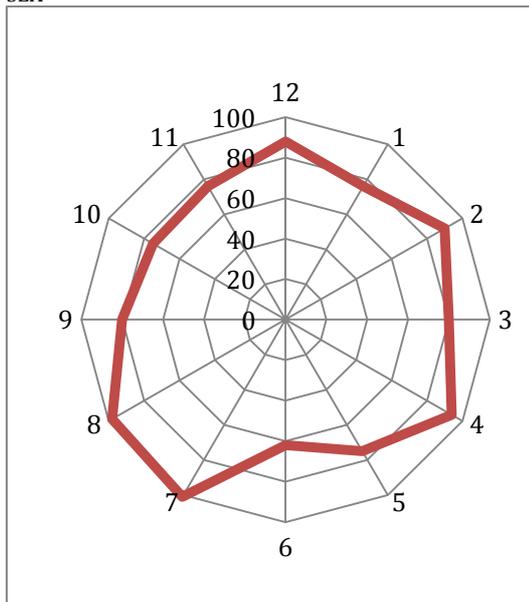
Pincer Case 14
SEA



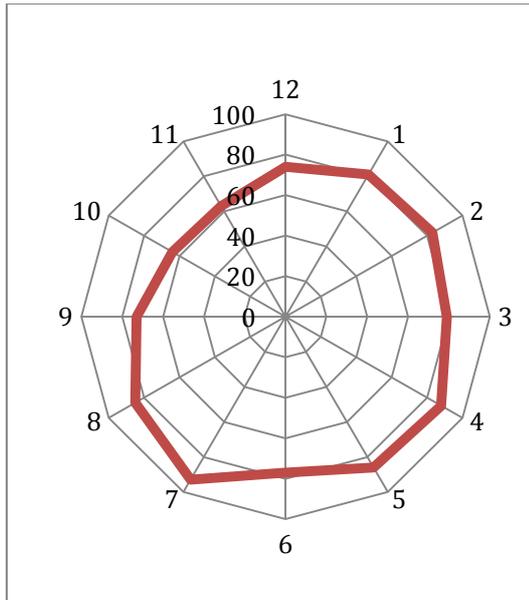
Mixed Case 1
SEA



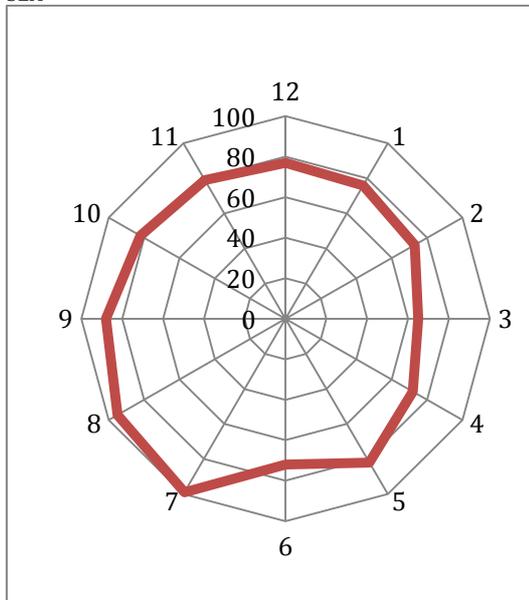
Mixed Case 2
SEA



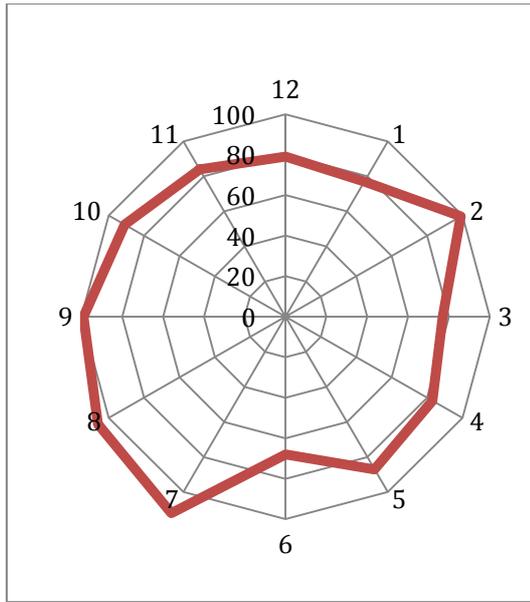
Mixed Case 3
SEA



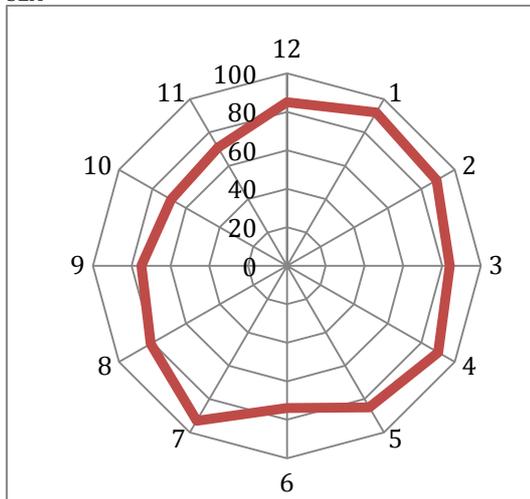
Mixed Case 4
SEA



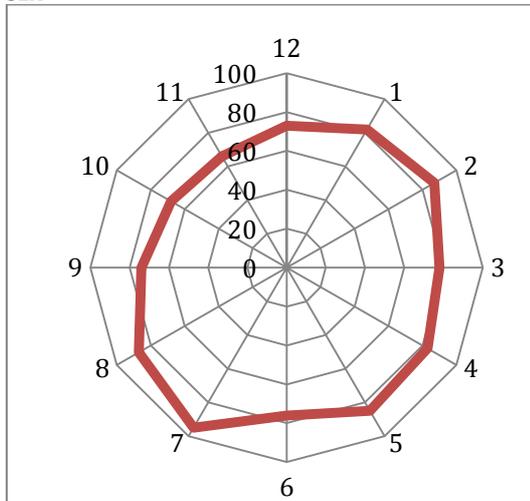
Mixed Case 5
SEA



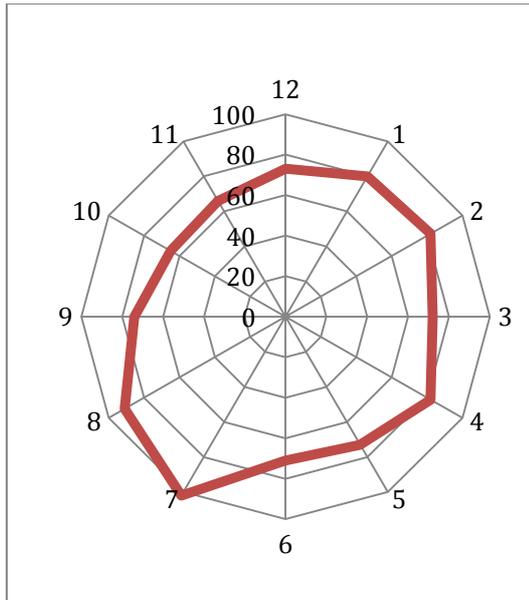
Mixed Case 6
SEA



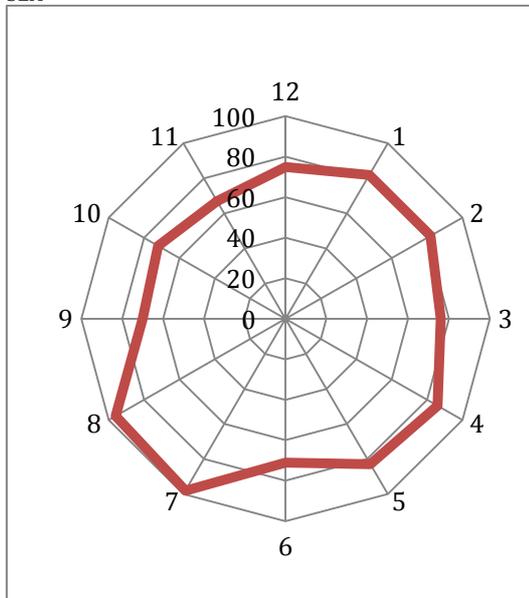
Mixed Case 7
SEA



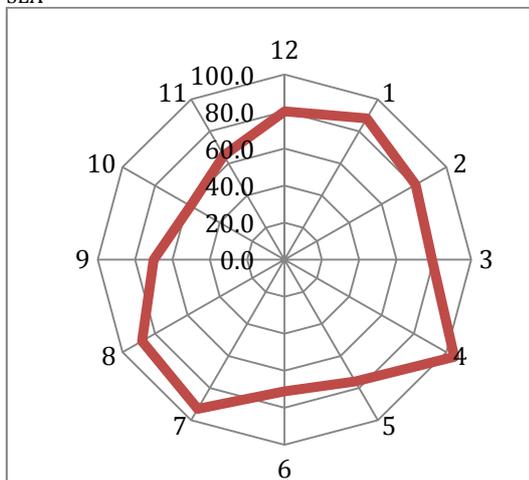
Mixed Case 8
SEA



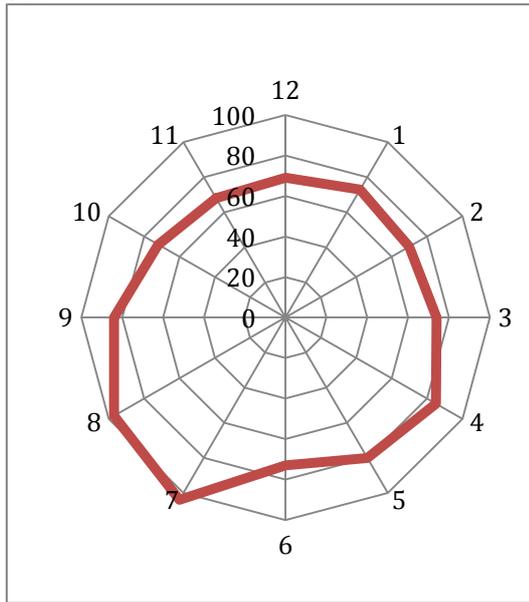
Mixed Case 9
SEA



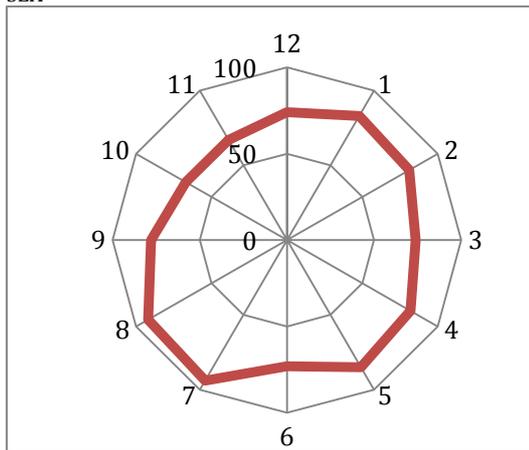
Mixed Case 10
SEA



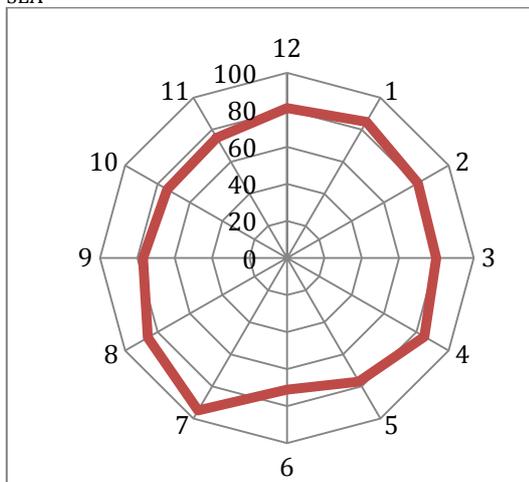
Mixed Case 11
SEA



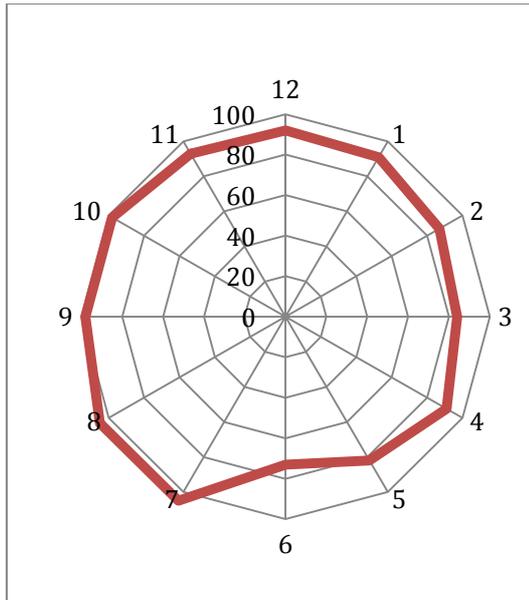
Mixed Case 12
SEA



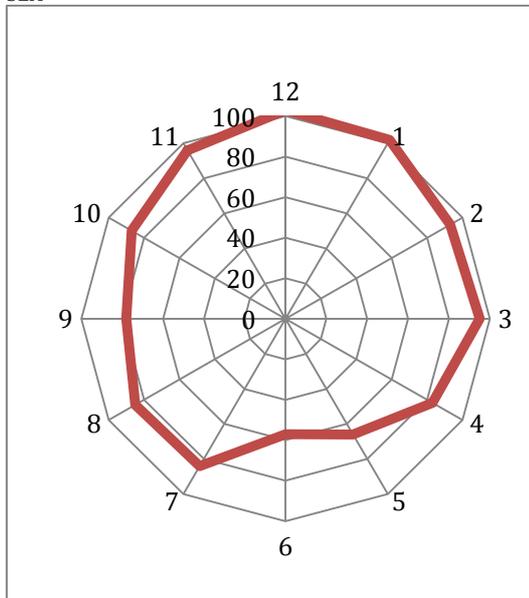
Mixed Case 13
SEA



Mixed Case 14
SEA

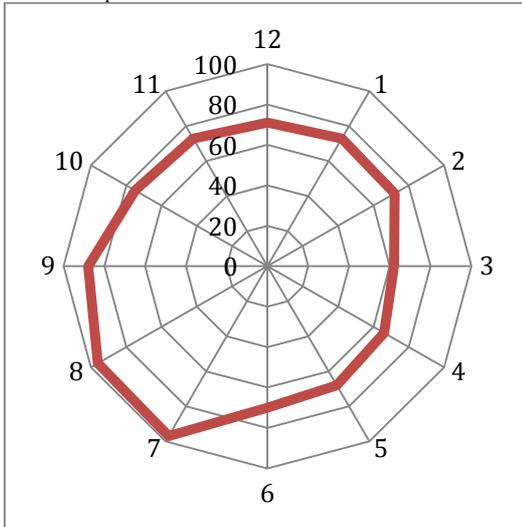


Mixed Case 15
SEA

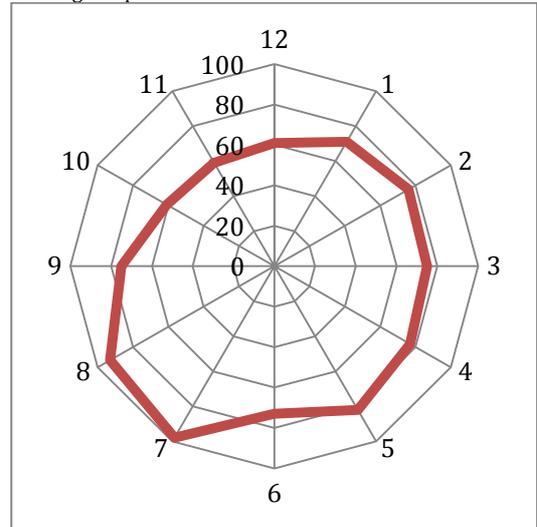


11.2.6 Radar plots for pincer morphology controls

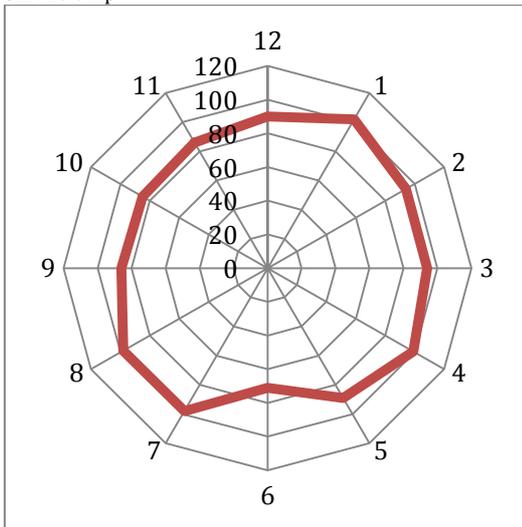
Pincer Control 1
SEA Left hip



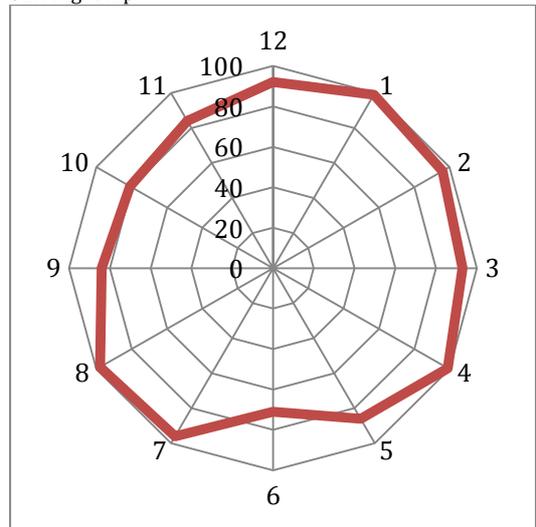
SEA Right hip



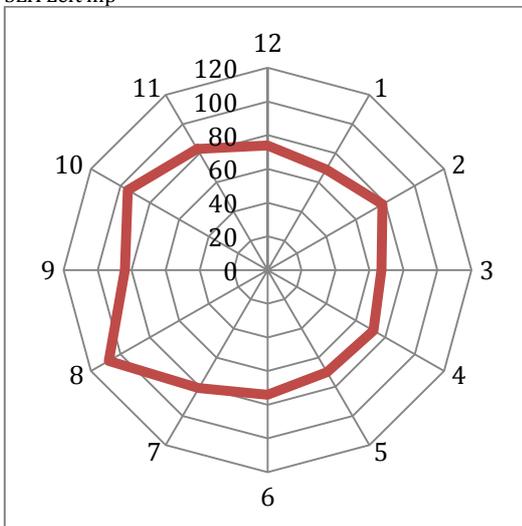
Pincer Control 2
SEA Left hip



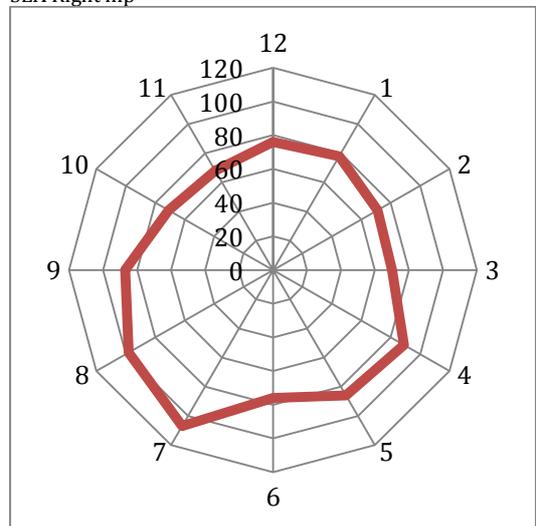
SEA Right hip



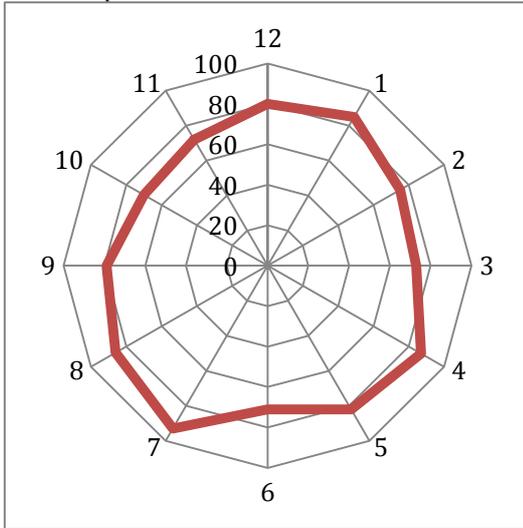
Pincer Control 3
SEA Left hip



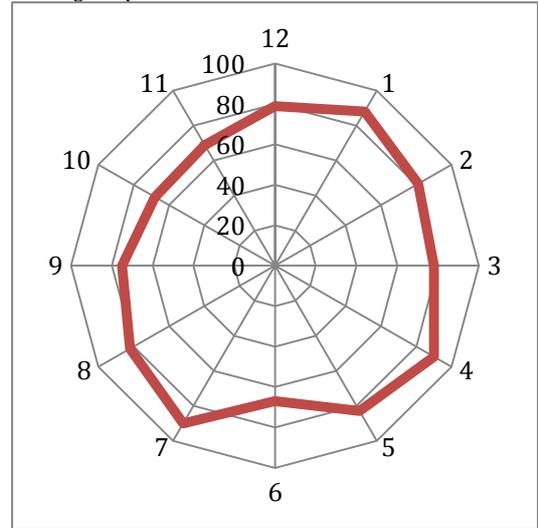
SEA Right hip



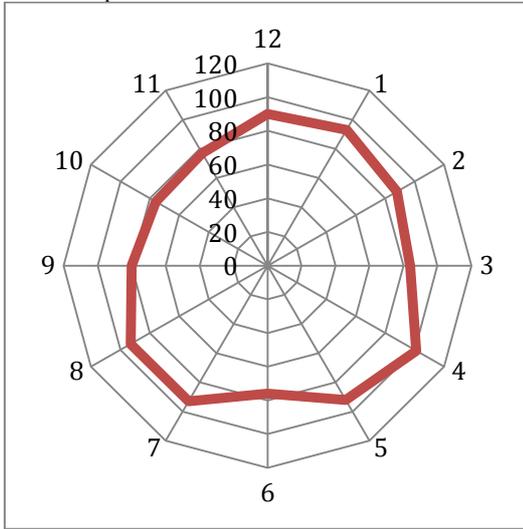
Pincer Control 4
SEA Left hip



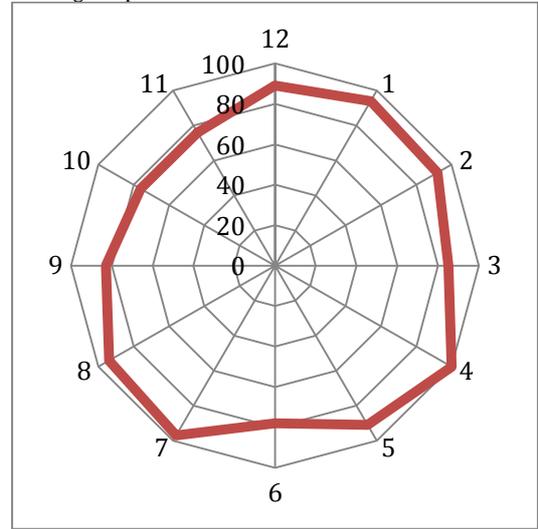
SEA Right hip



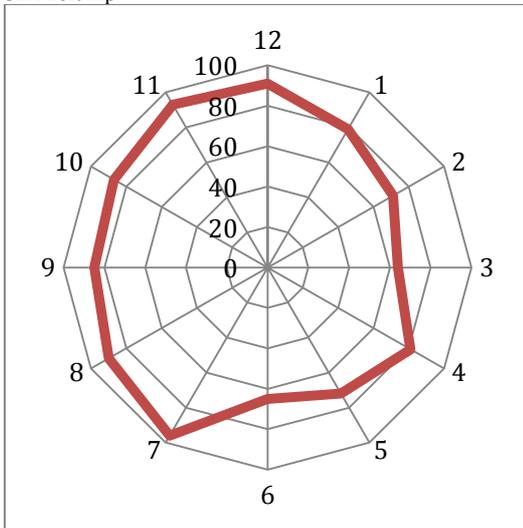
Pincer Control 5
SEA Left hip



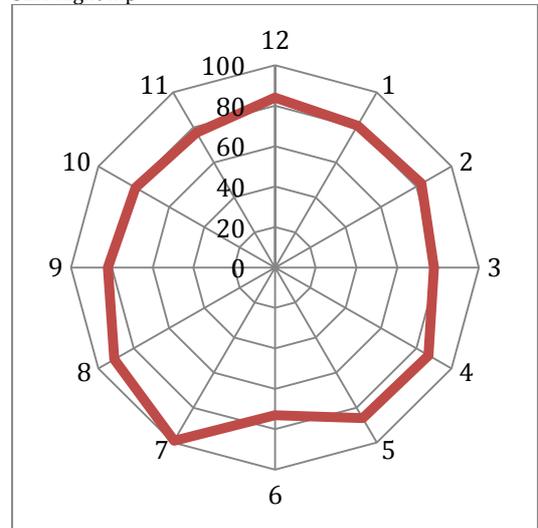
SEA Right hip



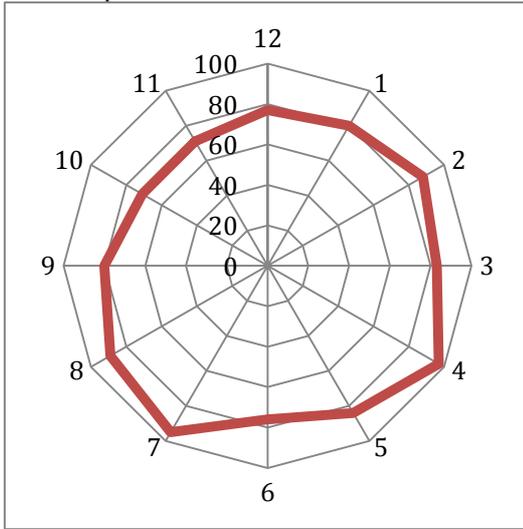
Pincer Control 6
SEA Left hip



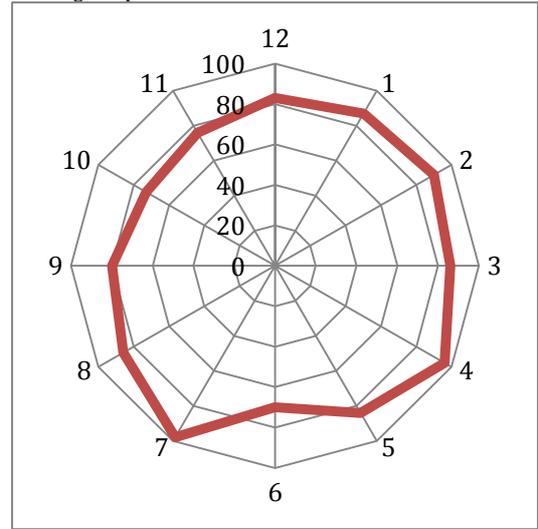
SEA Right hip



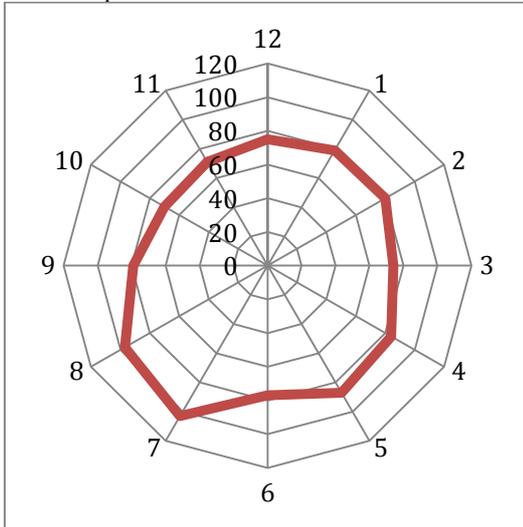
Pincer Control 7
SEA Left hip



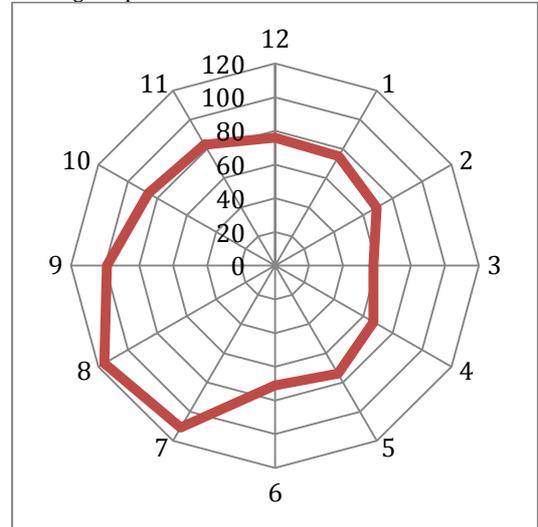
SEA Right hip



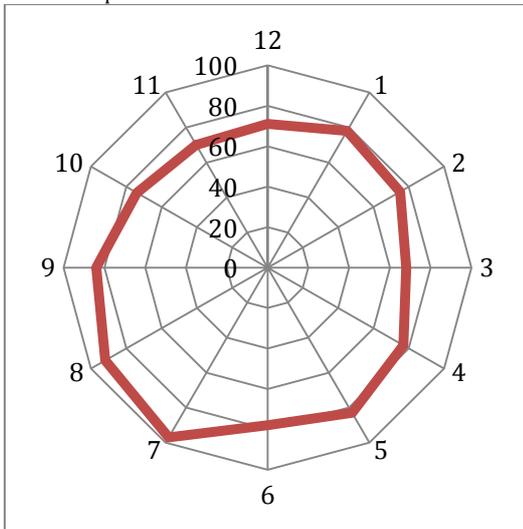
Pincer Control 8
SEA Left hip



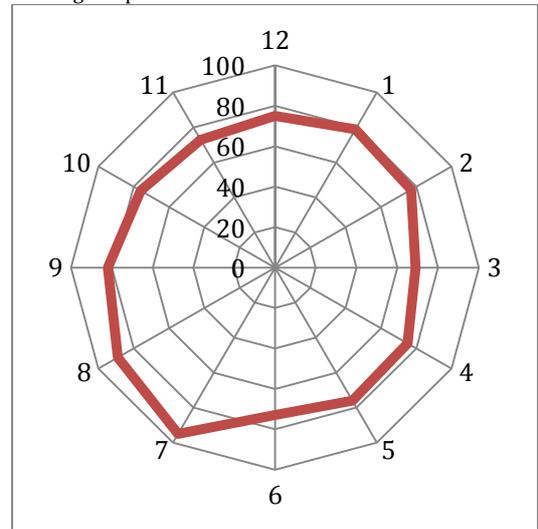
SEA Right hip



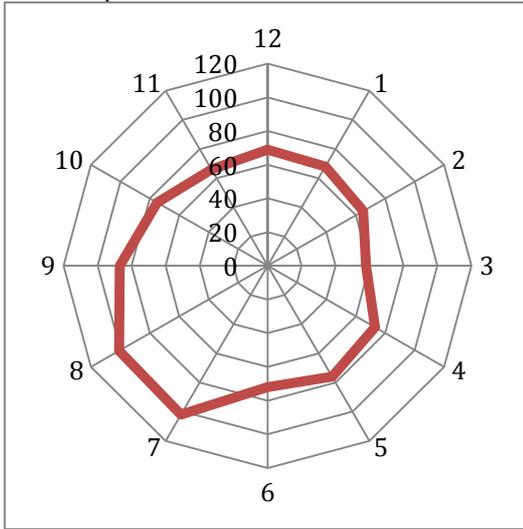
Pincer Control 9
SEA Left hip



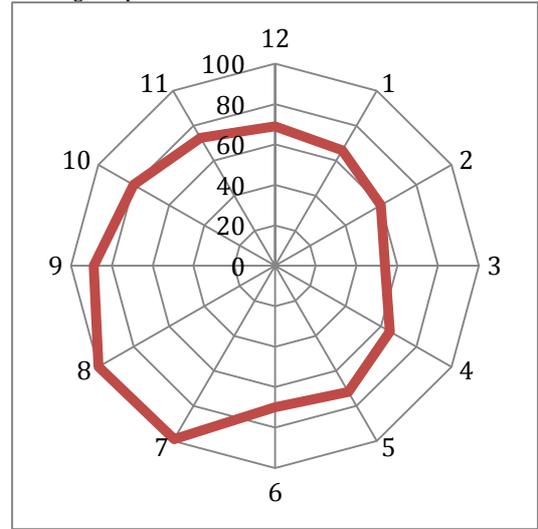
SEA Right hip



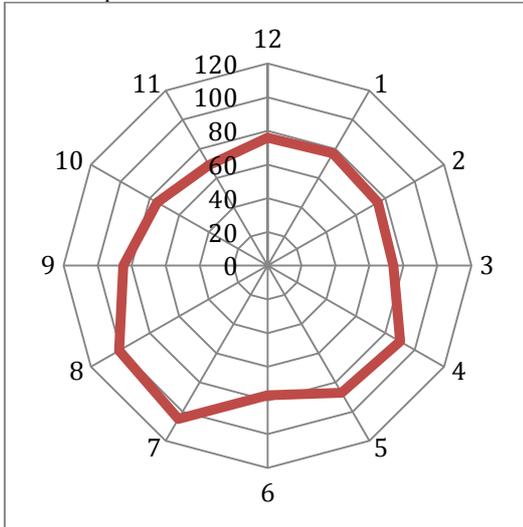
Pincer Control 10
SEA Left hip



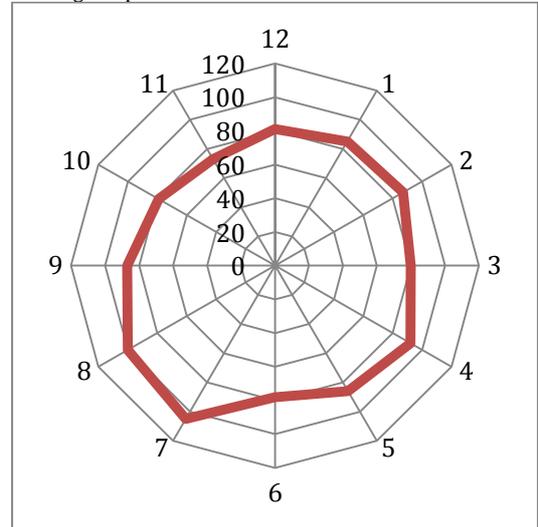
SEA Right hip



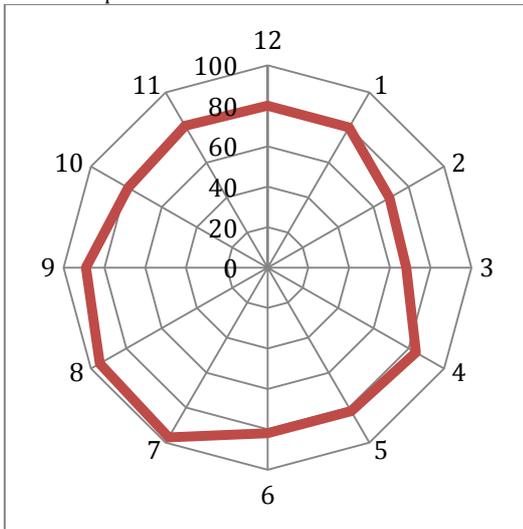
Pincer Control 11
SEA Left hip



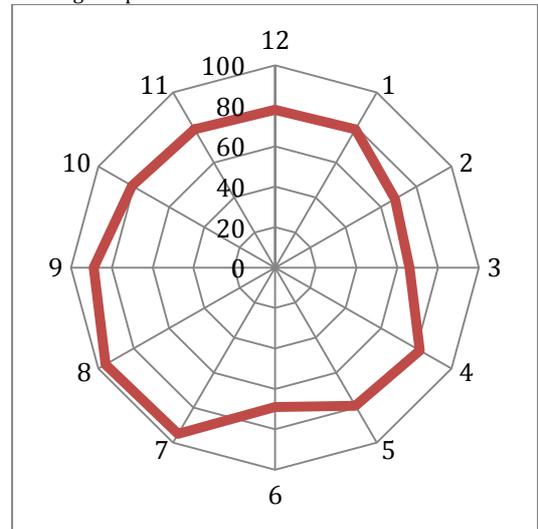
SEA Right hip



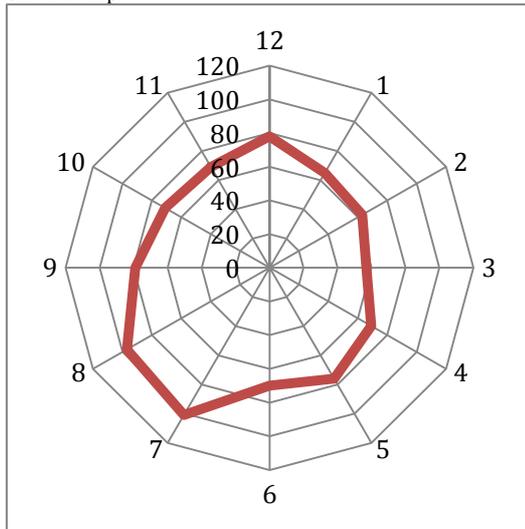
Pincer Control 12
SEA Left hip



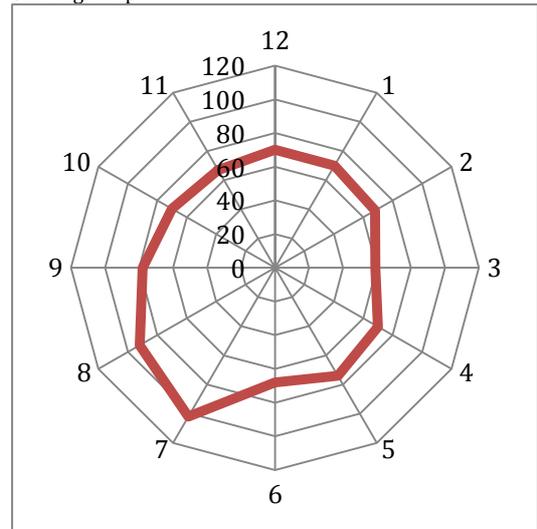
SEA Right hip



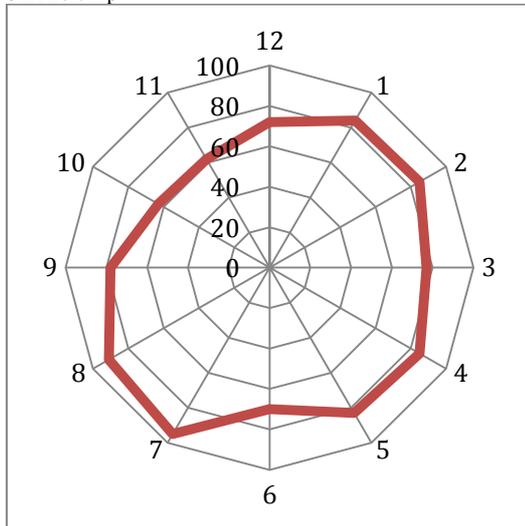
Pincer Control 13
SEA Left hip



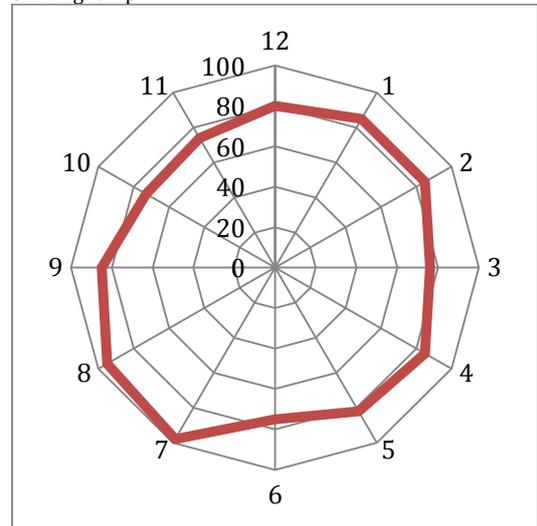
SEA Right hip



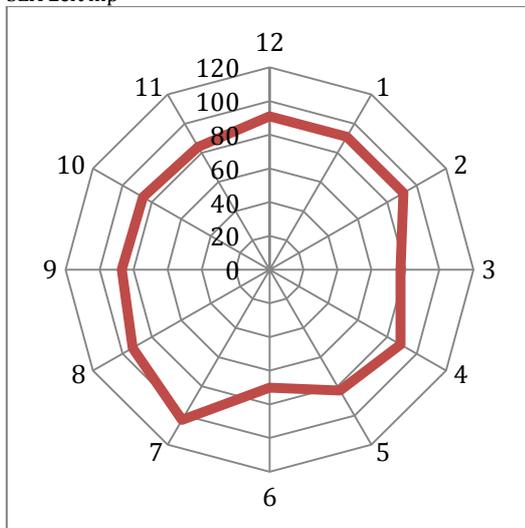
Pincer Control 14
SEA Left hip



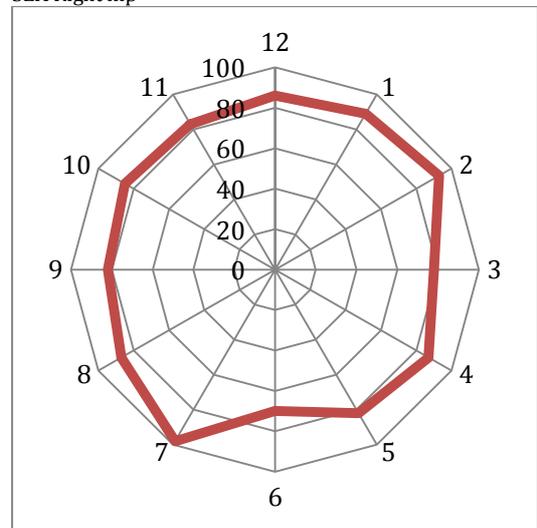
SEA Right hip



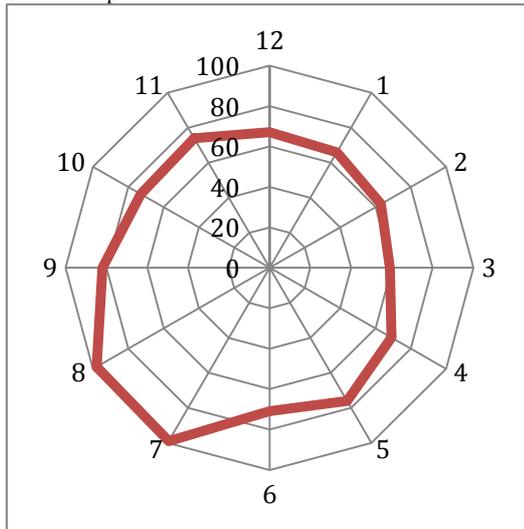
Pincer Control 15
SEA Left hip



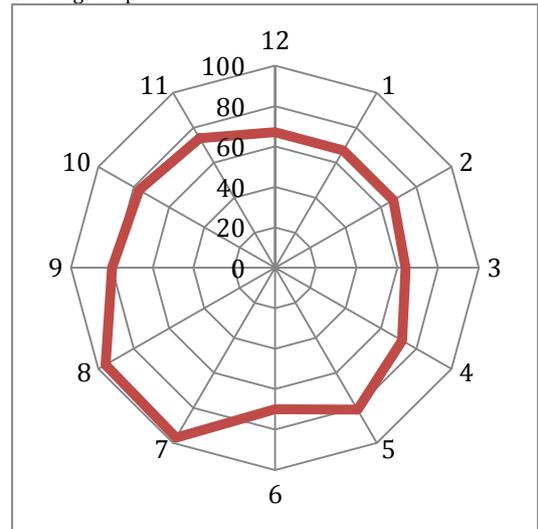
SEA Right hip



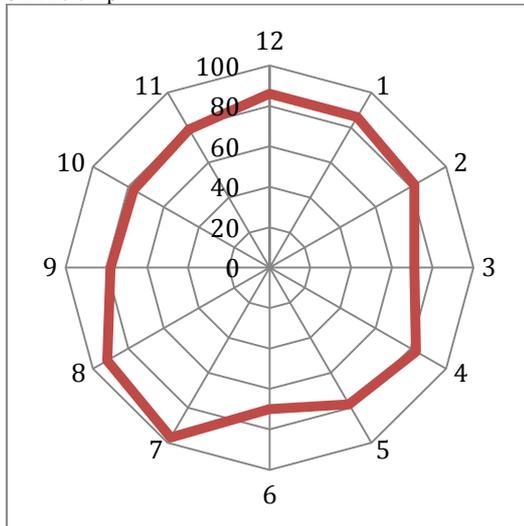
Pincer Control 16
SEA Left hip



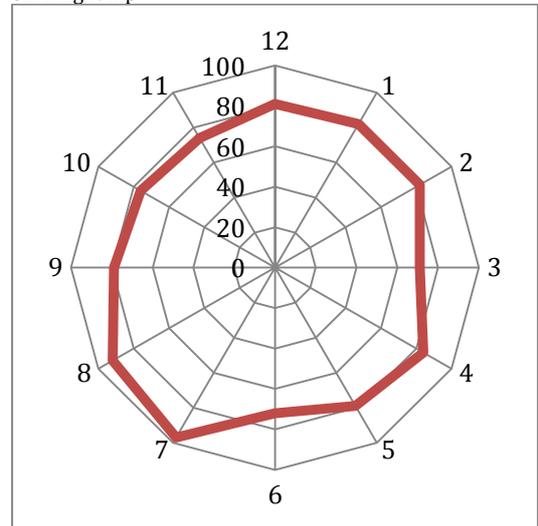
SEA Right hip



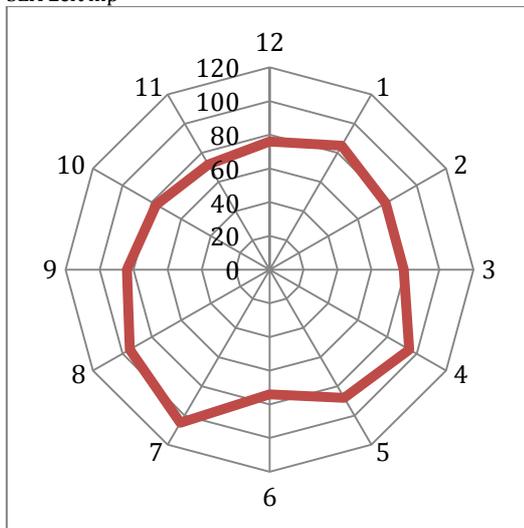
Pincer Control 17
SEA Left hip



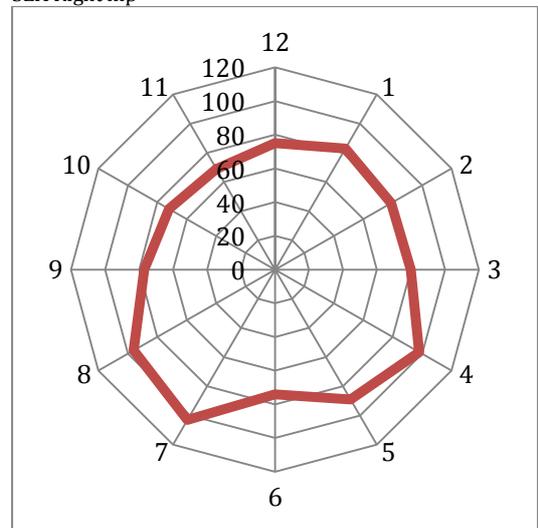
SEA Right hip



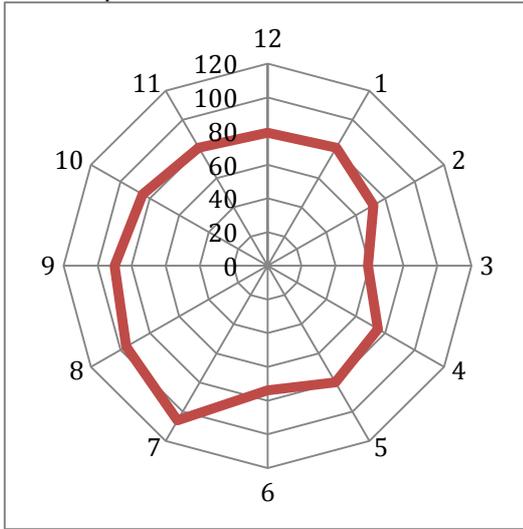
Pincer Control 18
SEA Left hip



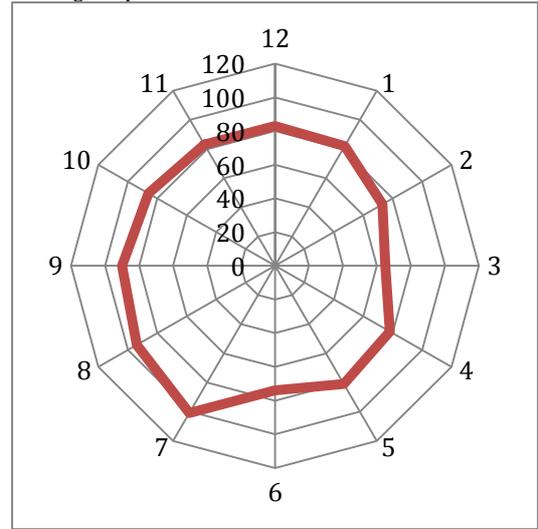
SEA Right hip



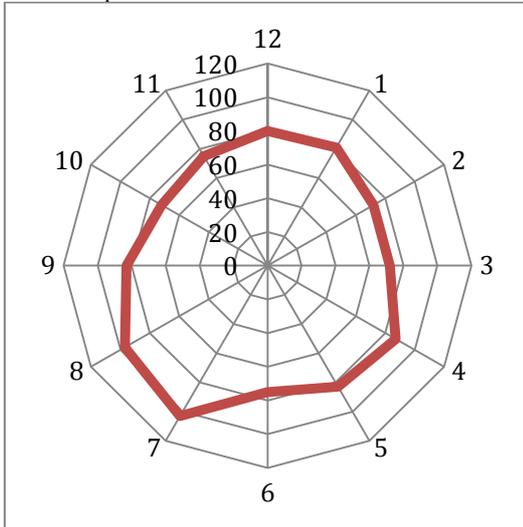
Pincer Control 19
SEA Left hip



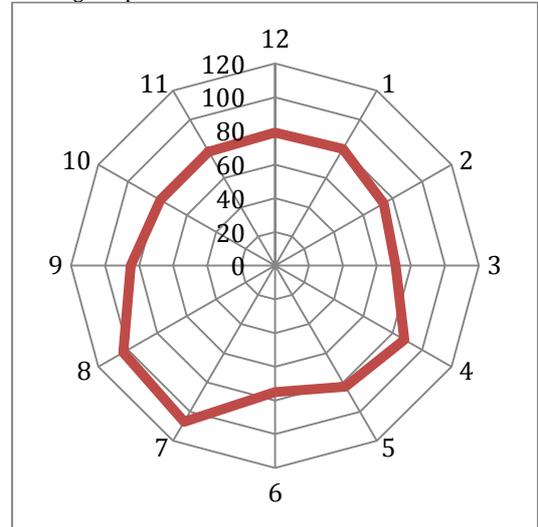
SEA Right hip



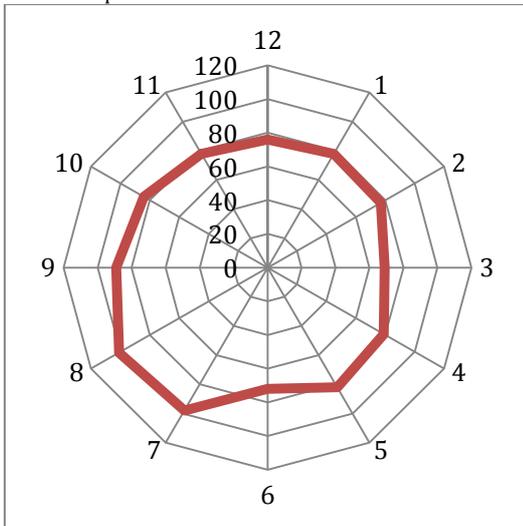
Pincer Control 20
SEA Left hip



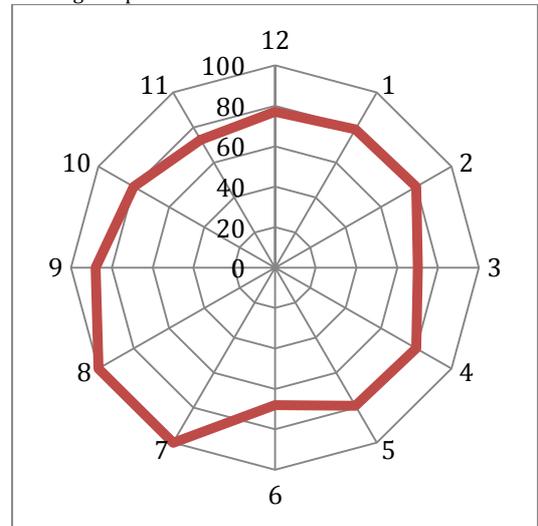
SEA Right hip



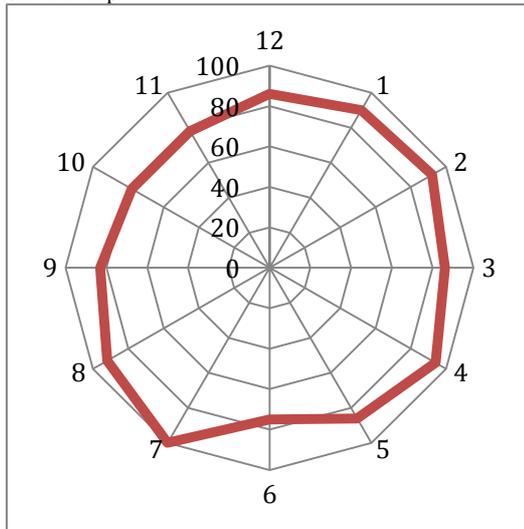
Pincer Control 21
SEA Left hip



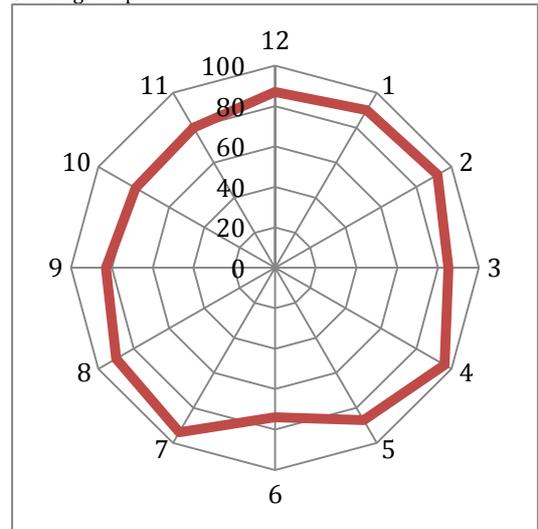
SEA Right hip



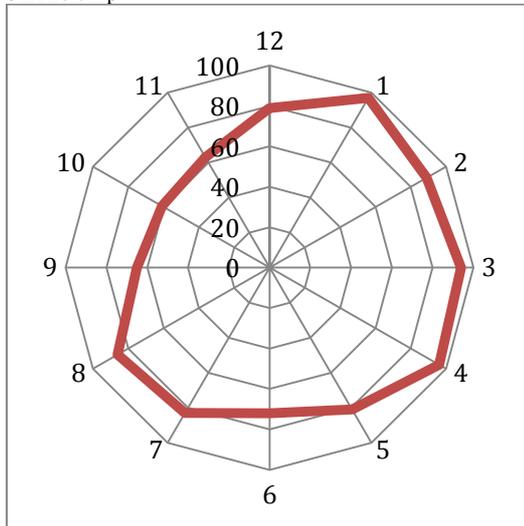
Pincer Control 22
SEA Left hip



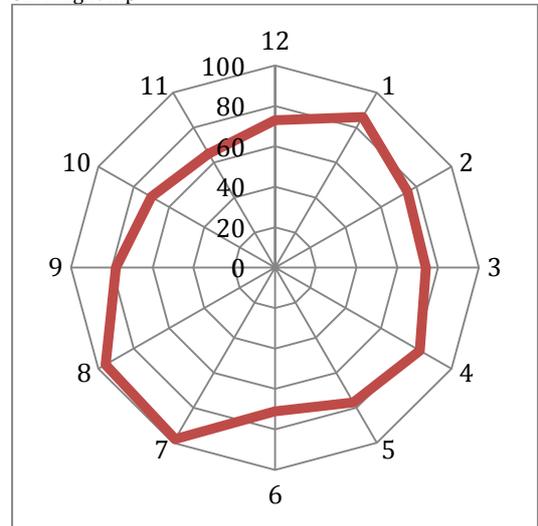
SEA Right hip



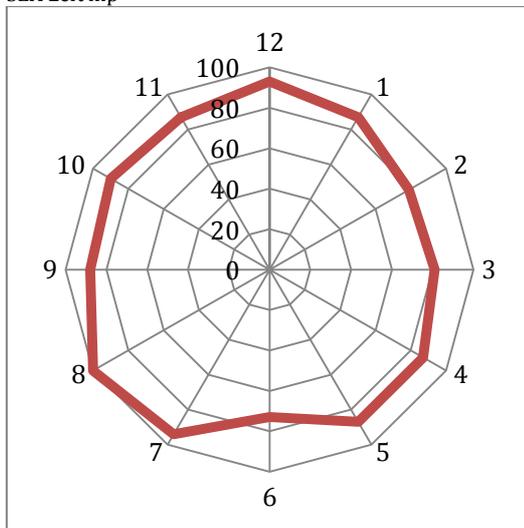
Pincer Control 23
SEA Left hip



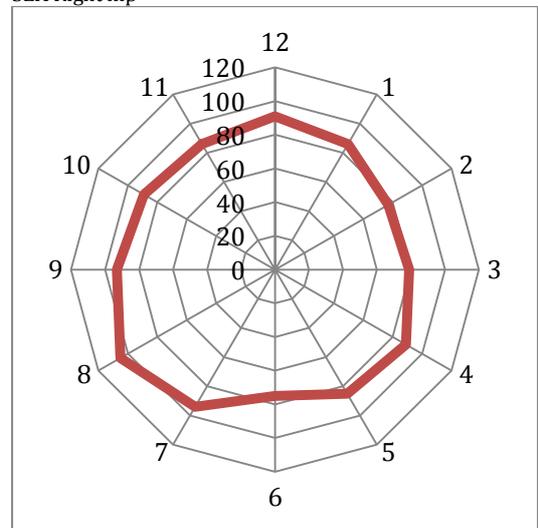
SEA Right hip



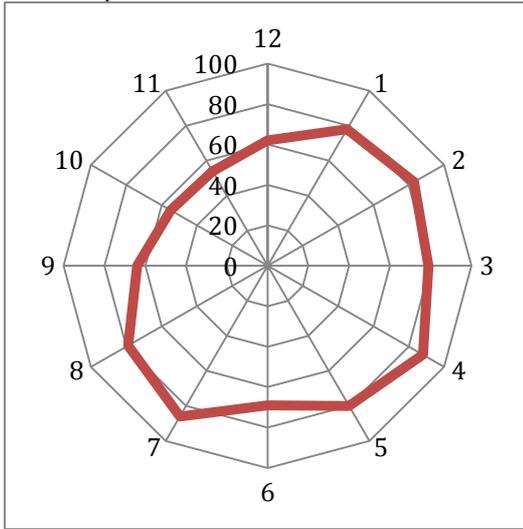
Pincer Control 24
SEA Left hip



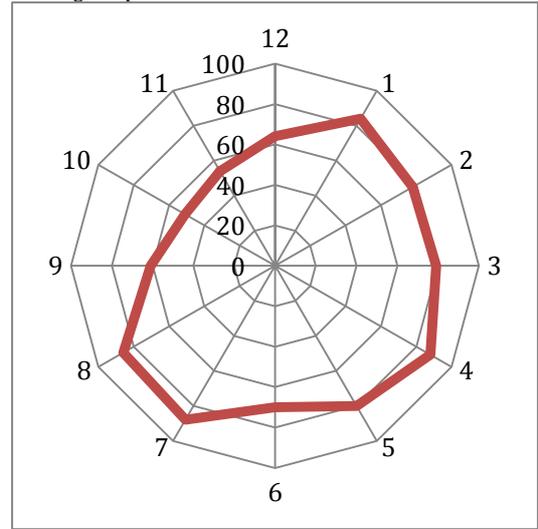
SEA Right hip



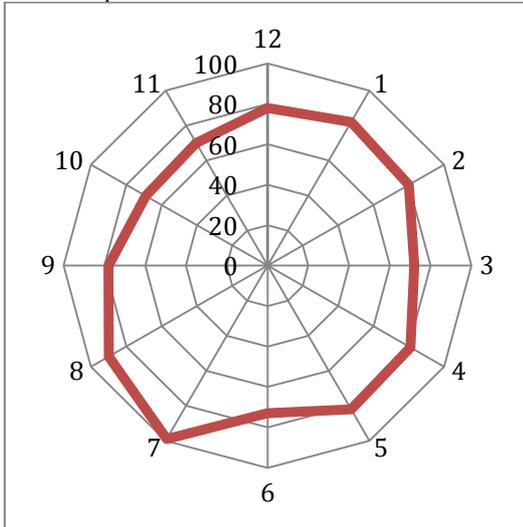
Pincer Control 25
SEA Left hip



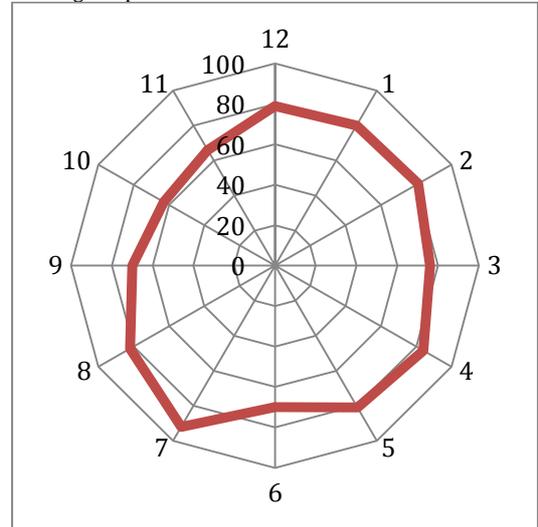
SEA Right hip



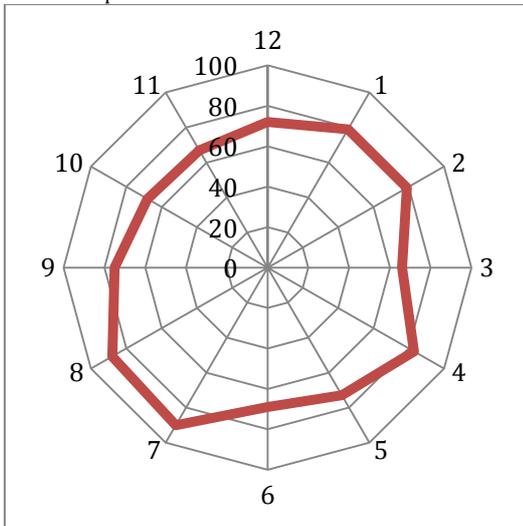
Pincer Control 26
SEA Left hip



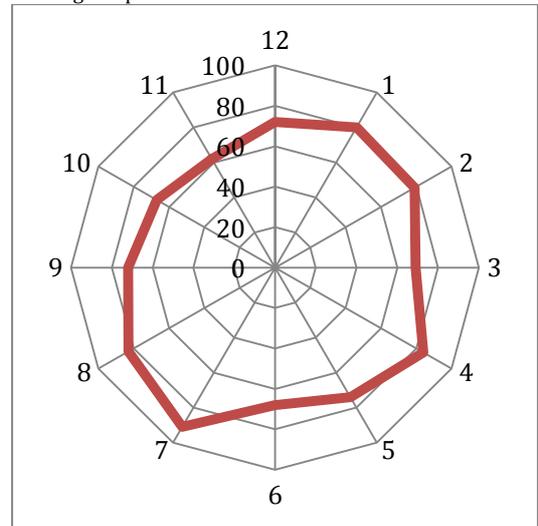
SEA Right hip



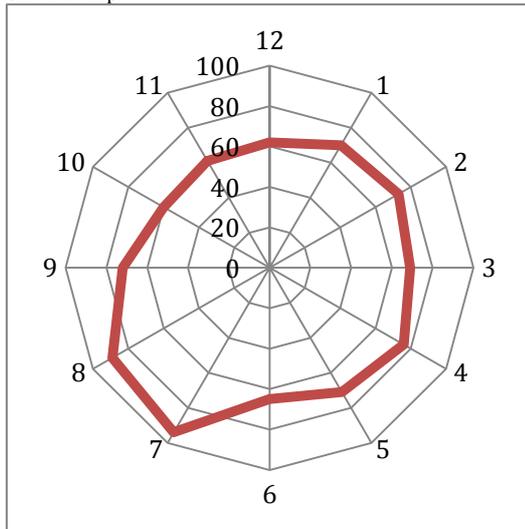
Pincer Control 27
SEA Left hip



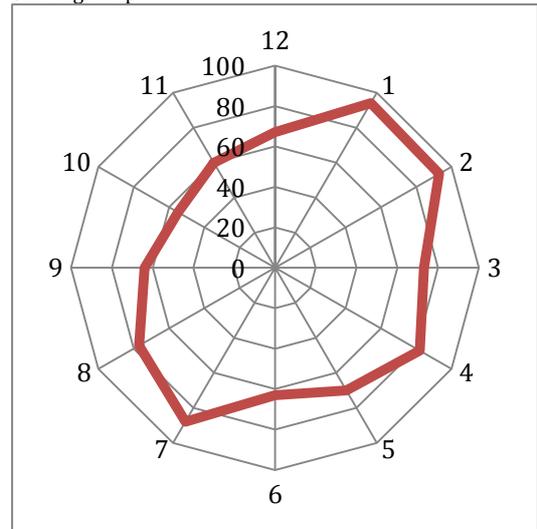
SEA Right hip



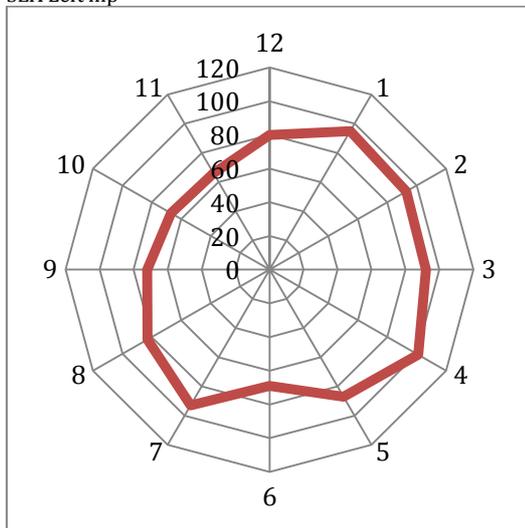
Pincer Control 28
SEA Left hip



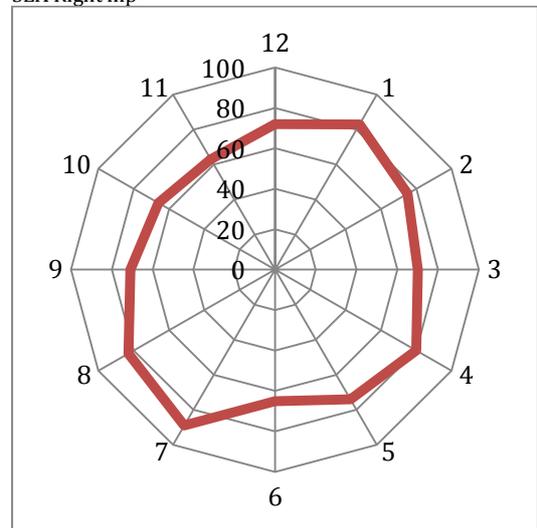
SEA Right hip



Pincer Control 29
SEA Left hip



SEA Right hip



11.3 Chapter 6 additional material

11.3.1 Cricketers Hips Study

Methods

This study was approved by the University of Warwick Biomedical Sciences Research Ethics Committee 8.10.14. The Chief Medical Officer of the England and Wales Cricket Board (ECB) gave approval for the study.

Participants

All cricketers attending a screening event at the ECB facility in Loughborough on 20-21st October 2014 were invited to participate. All players were England cricketers in the one day or twenty-twenty match squads who were attending a screening event prior to their winter tour.

Questionnaire Assessment

Players were asked to complete questionnaires that asked: date of birth, height, weight, smoking status, years as first class cricketer, if they have 'had any pain, lasting one day or longer in the preceding month', if so which hip and if they have previously had any hip disorders. Players also completed an iHOT12 questionnaire relevant to each hip.

Physical Assessment

A physical examination was undertaken in order to identify the players' range of hip flexion, adduction, abduction, internal rotation in 90° flexion (IR90) and external rotation in 90° flexion (ER90). The presence of flexion adduction internal rotation (FADIR) and flexion abduction external rotation impingement (FABER) signs was recorded.

MR Assessment

A mobile 1.5tesla (Siemens, Erlangen, Germany) MRI scanner was used to image both hips of each player. Image analysis was conducted in OSIRIX DICOM view (version 8 32 bit).

The proximal femur was assessed for signs of cam morphology by measuring alpha angles at 12, 130 and 3 o'clock. A mean of these measurements greater than 52° was considered cam morphology.

Signs of pincer morphology were assessed by measuring acetabular anteversion at the boundary between the superior ¼ and middle ¼ (acetabular anteversion 25%) on a coronal slice in the middle of the femoral head, and the boundary between the two middle quarters of the acetabulum (acetabular anteversion 50%). An anteversion less than 0° was considered pincer morphology. A CEA was also measured, a CEA greater than 40° was considered pincer morphology.

Analysis

Summary statistics were used to describe the results of the questionnaires, physical and MRI examinations. Due to the small sample size, no formal hypothesis testing was conducted. Prevalence estimates for cam and pincer morphology in the group of players are reported.

Results

Of the 18 players who attended the screening event, all completed the questionnaire. 16 players underwent physical examinations and 17 underwent MRI examination. The assessment took place after a period of 4 weeks where no cricket was played, and players were not formally training.

Two players reported hip pain (13%), one left hip and one right hip.

The median iHOT12 scores was 100. The lowest reported score was 52. The results of the questionnaire assessment, physical and MRI examination are displayed in Table 44.

Of the 14 players who underwent physical examination, 8 hips had a positive FADIR test and 1 hip had a positive FABER test.

Cam morphology was present in 18 hip (50%) and 10 (59%) players. Pincer morphology, secondary to retroversion was present in two players (12%) and two hips (12%). One player and one hip had pincer morphology secondary to a CEA greater 40°.

Table 44 Results of Crickets Questionnaire, physical and MRI examination

Test	Median	IQR
iHOT12/ score out of 100	94	96-100
Flexion/°	117	115-121
IR90 /°	31	27-33
ER90/°	27	25-31
alpha angles 12 o'clock	46	42-53
alpha angles 1,30 o'clock	57	50-65
alpha angles 3 o'clock	48	41-56
Acetabular anteversion 25%	14	6-18
Acetabular anteversion 50%	18	16-21
CEA	25	23-30

11.3.2 Golfers Hips; press release

August 2016

It is all in the hips

New study finds professional golfers more likely to have different shaped hip joints to most of the population

Lack of success on the fairway may not be due to your swing – it could be your hips that are to blame.

New research from the University of Warwick has found that professional golfers are more likely to have different shaped right and left hips compared to the rest of us.

The finding was made by Dr Edward Dickenson and his colleagues at the University of Warwick's Warwick Medical School. The research team, led by Professor Damian Griffin of the University of Warwick, have published two papers (*Hip morphology in elite golfers: asymmetry between lead and trail hips* and *Professional golfers' hips: prevalence and predictors of hip pain with clinical and MR examinations*) in a special Olympic golf themed issue of the British Journal of Sports Medicine, the top sports science and sports medicine journal in the world.

Elite golfers

The team originally set out to investigate hip problems in golfers. They were surprised to find that almost a fifth of European professional players reported hip pain. Further investigation found the pain appears to be related to the shape of the ball of their hips. Elite golfers were four times more likely to have an egg-shaped right hip (called cam morphology) compared to their left. These findings are unique to professional golfers; this pattern is not observed in the general population. The presence of cam morphology reduces the range of hip rotation, a movement required to generate power in the golf swing. The researchers found that golfers whose hips are more 'egg-shaped' were more likely to experience pain than those who have rounder 'ball-shaped' hips.

Dr Dickenson said: "Our findings have brought up new questions to be answered. What remains to be established is whether professional golfers develop these shapes because the way they are using their hips or whether players with these hip shapes are more likely to become professional."

The discovery comes in what is perhaps the biggest year in golf's recent history, with the Olympics, four Majors, and the Ryder Cup.

The Scottish Hydro Challenge

Professor Griffin, who also treats people with hip problems at University Hospitals of Coventry and Warwickshire NHS Trust added: "Golf is one of the most popular global sports with 57 million participants worldwide and four million in the UK. This new finding of asymmetry between the hips may explain differential rates of pain reported between the left and right hips in golfers. Beyond golf, it helps us to understand why and how hip pain due to femoroacetabular impingement syndrome develops in young active people."

The data for the study was collected at the Scottish Hydro Challenge, a European Challenge Tour event in Aviemore, Scotland in 2015. For the first time ever a portable MRI scanner was taken to a golfing event. The tournaments players were asked to complete a health questionnaire, be examined by Dr Dickenson and have an MRI scan of their hips. In total 55 players volunteered to undergo an MRI scan and it is these results that have revealed the difference in hip shape.

Cam morphology has been identified as a cause of femoroacetabular impingement syndrome, a condition that causes hip pain in young and active people. Professor Griffin and his team at Warwick Medical School have been researching this problem for many years, and he leads the FASHIoN trial, an international study to test keyhole surgery for femoroacetabular impingement syndrome. This is important because cam morphology and femoroacetabular impingement syndrome cause hip pain in many people, and are also associated with hip osteoarthritis later in life.

Hip joints

In the new study, cam morphology was found in 16% of right hips (the rear hip during a swing in a right handed player) and 4% of left hips (the front hip during the swing in a right handed player) in professional golfers. Golfers hip joints rotate in different directions and at different speeds during the golf swing. These findings of different shapes between hips go some way to explain differential rates of pain between the left and right hips in golfers.

Dr Andrew Murray, specialist sports doctor for the European golf tour said: “Overall, we know golf can provide considerable health benefits, with likely improved longevity, and better physical and mental health. But golf puts huge forces through the hips every time a player swings the club. The British Journal of Sports Medicine and the European and Challenge Tour golf have recognised these key challenges, and that quality research is required to look specifically at the hip joint in golfers. These papers, conducted with elite golfers have exciting new findings for the sport.”

The research was supported by the European Tour Performance Institute and by research grants from Orthopaedic Research UK and The Royal College of Radiologists.

ORUK Chief Executive Dr Arash Angadji said: “Effective collaboration between academia, the NHS and the third sector is vital to maximise the impact of research. We are increasingly focused on ensuring that the money we invest is given the best opportunity to translate into new, effective orthopaedic treatments and to deliver real benefits to patients.

“That was a key driver behind our decision to support this excellent research project which could lead to new and better diagnostic and treatment options, not just for golfers but for many people in the wider community.”

ENDS

Photo captions:

MRI scan indicating difference a high “alpha” angle of hip; a sign of cam morphology

3D reconstruction of a CT scan of right hip that shows the egg shaped ball

3D reconstruction of a CT scan of right hip with egg shaped ball shown front on

For further details please contact Nicola Jones, Media Relations Manager, University of Warwick 07920531221 or N.Jones.1@warwick.ac.uk

Notes to Editors:

British Journal of Sports Medicine:

1. Hip morphology in elite golfers: asymmetry between lead and trail hips
2. Professional golfers’ hips: prevalence and predictors of hip pain with clinical and MR examinations

DOI:

1. 10.1136/bjsports-2016-096007
2. 10.1136/bjsports-2016-096008

Authors:

1. E Dickenson, Medical School, Warwick Medical School; P O’Connor, Leeds Musculoskeletal Biomedical Imaging Unit, Leeds Teaching Hospitals; P Robinson, Leeds Musculoskeletal Biomedical Imaging Unit, Leeds Teaching Hospitals; R Campbell, Radiology Department, Royal Liverpool University Hospital, Liverpool; I Ahmed, Warwick Medical School; M Fernandez, Warwick Medical School; R Hawkes, C Hutchinson, D Griffin, Warwick Medical School.

2. E Dickenson, Clinical Trials Unit, Warwick Medical School; I Ahmed, Clinical Trials Unit, Warwick Medical School; M Fernandez, Clinical Trials Unit, Warwick Medical School; P O'Connor, Leeds Musculoskeletal Biomedical Imaging Unit Leeds Teaching Hospitals; P Robinson, Leeds Musculoskeletal Biomedical Imaging Unit, Leeds Teaching Hospitals; R Campbell, Radiology Department, Royal Liverpool University Hospital, Liverpool; A Murray, European Tour Performance Institute, European Tour, Virginia Water; M Warner, Faculty of Health Sciences, University of Southampton, Southampton; R Hawkes, European Tour Performance Institute, European Tour, Virginia Water; C Hutchinson, Department of Clinical Imaging, Warwick Medical School; D Griffin, Clinical Trials Unit, Warwick Medical School

Dr Edward Dickenson is currently a PhD student and Research Fellow at the University of Warwick, supervised by Professor Griffin. He is an Orthopaedic Registrar based at University Hospitals Coventry and Warwickshire.

Professor Damian Griffin is the Professor of Orthopaedic Surgery at Warwick Medical School, University of Warwick. He is also a Consultant Orthopaedic surgeon at University Hospitals of Coventry and Warwickshire NHS Trust, where he leads the Hip Preservation Surgery service, treating young and active people with hip problems.

The research was supported by the European Tour Performance Institute and by research grants from Orthopaedic Research UK and The Royal College of Radiologists.

11.3.3 Golfers Hips; mainstream media reports

BBC News Sport Weather iPlayer TV Radio

NEWS

Health

Golfers have unusual hips, study suggests

16 August 2016 | Health



THINKSTOCK

Professional golfers are likely to have oddly shaped hip joints, researchers have discovered.

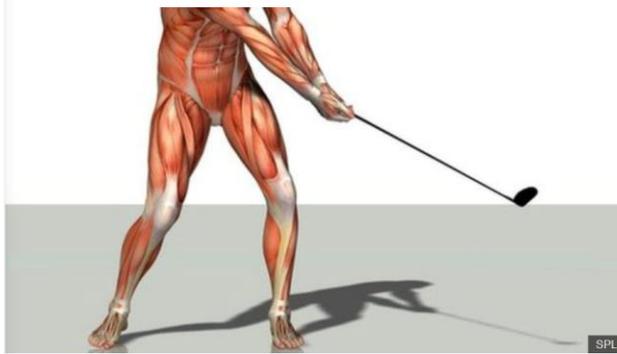
The University of Warwick team put 55 elite players into medical MRI scanners and, to their surprise, found many had egg-shaped right hips while their left joints were the usual ball shape.

Whether golfing causes the deformity or not is unclear, they say in the [British Journal of Sports Medicine](#).

Almost a fifth of the 2015 Scottish Hydro Challenge players had **hip pain**.

Lead researcher Prof Damian Griffin said shape mismatch between the hips might explain some of the pain reported by the golfers.

Dr Andrew Murray, specialist sports doctor for the European golf tour, said: "Overall, we know golf can provide considerable health benefits, with likely improved longevity, and better physical and mental health. But golf puts huge forces through the hips every time a player swings the club."



When a golfer takes a swing at the ball, the two hips rotate in different directions and at different speeds.

The egg shape seen on some of the scans was visible in 16% of right hips - the rear hip during a swing in a right-handed player - and 4% of left hips - the front hip during the swing in a right-handed player - in the professional golfers.

The condition, known as cam rotation, reduces the natural range of movement of the hip.

Co-researcher Dr Edward Dickenson said: "Our findings have brought up new questions to be answered.

"What remains to be established is whether professional golfers develop these shapes because of the way they are using their hips or whether players with these hip shapes are more likely to become professional."

The Telegraph

ALL SECTIONS

Science

Science

Practising your golf swing could lead to hip problems and 'egg-shaped' joints, experts warn



Justin Rose could be suffering from an egg-shaped hip

By Sarah Knapton, SCIENCE EDITOR

16 AUGUST 2016 - 6:20PM

Practising your golf swing could lead to hip damage, sportsmen have been warned, after a study found that elite golfers are more likely to have egg-shaped joints.

Research from the University of Warwick found that professional golfers are more likely to have different shaped right and left hips compared to the general population.

One theory is that constantly practising golf swings may induce a change on one side, causing the ball joint in the hip to become more egg-shaped.



The researchers are unsure whether the hip problems are caused by golf

The team originally set out to investigate hip problems in golfers but were surprised

to find that almost a fifth of European professional players reported hip pain.

Further investigation found the pain appears to be related to the shape of the ball of their hips. Elite golfers were four times more likely to have an egg-shaped right hip, known as cam morphology, compared to their left.

Golfers whose hips are more 'egg-shaped' were found to be more likely to experience pain than those who have rounder 'ball-shaped' hips.



An egg-shaped hip joint which could lead to a painful swing

The findings are unique to professional golfers and is not observed in non golfers.

The presence of cam morphology reduces the range of hip rotation, a movement required to generate power in the golf swing.

Dr Andrew Murray, specialist sports doctor for the European golf tour said: "Overall, we know golf can provide considerable health benefits, with likely improved longevity, and better physical and mental health.



A normal ball-shaped joint

"But golf puts huge forces through the hips every time a player swings the club. "The British Journal of Sports Medicine and the European and Challenge Tour golf have recognised these key challenges, and that quality research is required to look specifically at the hip joint in golfers."

Lead researcher Dr Edward Dickenson said: "Our findings have brought up new questions to be answered.



"What remains to be established is whether professional golfers develop these shapes because the way they are using their hips or whether players with these hip shapes are more likely to become professional."

The data for the study was collected at the Scottish Hydro Challenge, a European Challenge Tour event in Aviemore, Scotland in 2015.



For the first time ever a portable MRI scanner was used to scan the hips of 55 players. They found egg-shaped 'balls' in 16 per cent of right hips, the rear hip during a swing in a right handed player, and in just 4 per cent of left hips.

The research was published in the *British Journal of Sports Medicine*.