

Manuscript version: Author's Accepted Manuscript

The version presented in WRAP is the author's accepted manuscript and may differ from the published version or Version of Record.

Persistent WRAP URL:

<http://wrap.warwick.ac.uk/110855>

How to cite:

Please refer to published version for the most recent bibliographic citation information. If a published version is known of, the repository item page linked to above, will contain details on accessing it.

Copyright and reuse:

The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:

Please refer to the repository item page, publisher's statement section, for further information.

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

Examining the Influence of Grip Type on Wrist and Club Head Kinematics during the Golf
Swing: Benefits of a Local Co-ordinate System

Howie J. Carson^{1*}, Jim Richards² and Bruno Mazuquin³

¹ Institute for Coaching and Performance, University of Central Lancashire, Preston, United Kingdom

² Allied Health Research Unit, University of Central Lancashire, Preston, United Kingdom

³ Warwick Clinical Trials Unit, University of Warwick, United Kingdom

*Correspondence concerning this article should be addressed to Howie J. Carson, 006 Greenbank Building, Institute for Coaching and Performance, University of Central Lancashire, Preston, PR1 2HE. E-mail: HCarson1@uclan.ac.uk

Abstract

1
2 Wrists movements have been identified as an important factor in producing a successful golf
3 swing, with their complex motion influencing both club head velocity and orientation.
4 However, a detailed analysis of wrist angles is lacking in the literature. The purpose of this
5 study was to determine kinematics across wrists and club head characteristics during the golf
6 swing under weak, neutral and strong grip conditions. Twelve professional male golfers
7 executed 24 shots using a driver under three grip conditions. A six degrees of freedom
8 analysis of the hand with respect to the distal forearm was performed using a 10-camera
9 three-dimensional motion capture system. Differences in joint angles were explored using
10 repeated measures ANOVAs at key swing events (onset, top of backswing and impact), in
11 addition club head velocity and clubface angle at impact were also explored. Main findings
12 revealed significant differences in flexion/extension and internal/external rotation for both
13 wrists at all swing events, whereas fewer significant interactions were found in ulnar/radial
14 deviation across grips for both wrists at all events. Clubface angle only differed significantly
15 between the weak and the strong and neural grips, presenting a more 'open' clubface to the
16 intended hitting direction. This study is the first to explore tri-planar wrist movement and the
17 effect of different grips, such analysis has implications for coaching knowledge and practice
18 and should inform future research into different aspects of skill, technique analysis and may
19 inform injury mechanisms/prevention.

20

21 *Keywords:* driver, golf, Qualisys, internal/external rotation, range of motion, six
22 degrees of freedom analysis.

23

24 Examining the Influence of Different Grip Types on Wrist and Club Head Kinematics during
25 the Golf Swing: Benefits of a Local Co-ordinate System

26 Wrist movements have been identified as an important factor in the production of a
27 successful golf swing, with their complex range of motion (ROM) influencing both club head
28 velocity and orientation (Nesbit, 2005; PGA, 2008; Sprigings & Neal, 2000). They have also
29 been identified as having the greatest angular velocities of all joints during the golf swing
30 (Zheng, Barrentine, Fleisig, & Andrews, 2008) and are consistently reported as the primary
31 injury site, particularly in the lead wrist (left in right-handed golfers), amongst high-level
32 golfers (Barclay, West, Shoaib, Morrissey, & Langdown, 2011; McCarroll, Retting, &
33 Shelbourne, 1990). For example, Barclay et al. reported within an international survey of 526
34 club and touring professionals a 66% prevalence of injury and within that sample a 44%
35 incidence rate pertaining to the wrist. Therefore, it is important that sport practitioners are
36 able to understand the nature of high-level golfers' lead and trail wrist kinematics during the
37 golf swing. Consequently, this may offer a useful insight into the mechanisms of wrist
38 injuries and a more detailed understanding of technique effectiveness.

39 To date, studies reporting three-dimensional wrist kinematics have been either
40 forward dynamic (MacKenzie & Sprigings, 2009; Sprigings & Neal, 2000) or experimental
41 (Cahalan, Cooney III, Tamai, & Chao, 1991; Fedorcik, Queen, Abbey, Moorman Iii, & Ruch,
42 2012; Zheng et al., 2008). However, little data exists on high- or elite-level golfers. Two
43 studies that have reported findings from high-level participants are Zheng et al. (2008) and
44 Fedorcik et al. (2012). Despite inclusion of high-level participants, data reported does not
45 allow a complete analysis of wrist mechanics. Zheng et al. (2008) defined the wrist by the
46 golf club shaft moving relative to the forearm, which is unlikely to provide a complete
47 understanding about the three-dimensional movement patterns. This would also partly
48 explain why previous data only exists in one or two axes of rotation; ulnar/radial deviation

49 and flexion/extension (Fedorcik et al., 2012; Nesbit, 2005; Zheng et al., 2008). Further
50 investigating the wrists' three-dimensional movement patterns could prove beneficial in
51 understanding different strategies and their relationship to golf swing effectiveness.

52 Indeed, non-sporting studies have previously reported ROM in internal/external
53 rotation about the wrist joint independently of forearm pronation/supination at the radioulnar
54 joint. Gilmour, Richards and Redfern (2012) examined wrist kinematics during activities of
55 daily living (ADL; e.g., opening/closing jars). Results from 9 healthy participants, which
56 were reported and published as part of a conference proceeding, revealed a maximum mean
57 ROM of 31.7°. Indeed, this finding is consistent with other studies using simulated ADL,
58 where a mean radiometacarpal internal/external rotation (ROM) of 34.1° was reported (Gupta
59 & Moosawi, 2005). Notably, it is acknowledged that wrist joint internal/external rotation is
60 passively controlled (i.e., voluntary forearm rotation does not independently axially rotate the
61 wrist joint) when performing ADL and external resistance is applied. In Gilmour et al.'s
62 (2012) study, resistance was applied by the objects being manipulated; and Gupta and
63 Moosawi (2005) actively forced rotation of the forearm by fixing the position of the
64 phalanges. It is likely that the inertial moments caused by the club accelerations during the
65 golf swing and/or the hands' orientation when gripping the handle, may also result in such
66 rotation. Therefore, wrist joint internal/external rotation should be included in future three-
67 dimensional analyses to allow for greater understanding.

68 Furthermore, existing research is limited by the amount of data provided during the
69 golf swing. Previous studies have only reported data at specific events such as the top of the
70 backswing and impact (e.g., Zheng et al., 2008). Despite this, studies have identified a
71 common feature for the lead wrist amongst high-level golfers when compared to novices.
72 Data indicate high-level golfers to be more radially deviated at the top of the backswing,
73 coupled with a delayed transition to ulnar deviation during the downswing until impact

74 (Lindsay, Mantrop, & Vandervoort, 2008; Sharp, 2009; Sprigings & Neal, 2000). According
75 to the Training Academy of The Professional Golfers' Association (PGA) of Great Britain
76 and Ireland, these events represent the swing principle 'release,' which describes returning
77 the clubface back in line with the target through the "impact position while freeing the power
78 created in the backswing" (PGA, 2008, p. 48), which are important to both distance and
79 accuracy. However, what appears to be lacking in the literature is a detailed three-
80 dimensional analysis for both wrists during the entire golf swing and their relationship with
81 club head measures at impact, and the effect of different grip types, often described by the
82 address position. For example, a 'strong' grip presents the palm of the lead hand more on top
83 of the handle and the trail hand more underneath, versus a 'weak' grip with the palm of the
84 lead hand rotated anticlockwise around the handle and the trail hand more on top (see Figure
85 1). A weak grip (and vice versa for a strong grip) is described as such due to its apparent
86 limiting influence on wrist 'action'/release, therefore reducing ball carry distance (Najar,
87 2010). Furthermore, golf coaching texts explain that the direction of clubface alignment at
88 impact, relative to the intended target line, can be associated with grip type (PGA, 2010),
89 which can be inferred by the extent of lead wrist flexion/extension at the top of the
90 backswing. Addressing the latter, greater extension indicates a likely 'open' clubface and
91 flexion a likely 'closed' clubface (Haney, 2012; PGA, 2008). Consequently, it is possible
92 that some golfers may attempt adjustments to their grip to facilitate different shot shapes. If a
93 complete three-dimensional analysis of the wrist joints were able to provide increased detail
94 across the three planes of motion, it may be possible to assess for any exact changes in the
95 wrist kinematics as a result of different starting grip techniques.

96

97

****Figure 1 here****

98

124 knuckles on each hand at the address position as shown in Figure 1. Accordingly, eight full
125 swing executions were captured from each participant utilising a neutral, strong and weak
126 grip technique.

127 Kinematic data were collected using 10 Oqus 700 cameras (Qualisys Medical AB,
128 Sweden) at a sampling rate of 300 Hz. Qualisys Track Manager™ (QTM, Version 2.11,
129 Qualisys Medical Ltd., Sweden) was used to reconstruct the three-dimensional co-ordinates
130 of 10 mm passive retro-reflective markers applied bilaterally to the following anatomical
131 sites: medial and lateral humerus epicondyles, radial and ulnar styloid processes and 2nd and
132 5th metacarpal heads. Rigid clusters were positioned on the distal forearms and dorsum of the
133 hands allowed segmental tracking in six degrees-of-freedom. Seven 6 mm markers were
134 positioned on the four extremities of the clubface and three on the club head; the ball was
135 also marked with retro-reflective tape. Four 10 mm passive retro-reflective markers were
136 affixed onto the artificial turf mat in a cross formation to enable club head orientation and
137 velocity to be calculated (Figure 2). A neutral static calibration trial was captured prior to
138 testing with the participant adopting the anatomical position for 1 s, markers positioned at
139 anatomical landmarks were subsequently removed prior to golf swing executions.

140

141 ***Figure 2 here***

142

143 **Data Processing**

144 Raw kinematic data for a minimum of five trials from each condition per participant
145 were exported into c3d file format and analysed using Visual 3D v5.01.25 software (C-
146 Motion Inc., USA). Co-ordinate systems were assigned using joint centres defined by the
147 medial and lateral markers on the proximal and distal aspects for each segment using a single
148 frame of the static calibration trial (y -axis = anterior–posterior, x -axis = medial–lateral and z -

149 axis = proximal–distal). The radioulnar segments were defined proximally using the medial
150 and lateral humerus epicondyles and distally using the radial and ulnar styloid processes. The
151 hands were defined proximally using the radial and ulnar styloid processes and distally using
152 the 2nd and 5th metacarpal heads. Wrist joint angles were calculated in all three axes of
153 rotation of the distal segment relative to the local co-ordinate system (LCS) of the proximal
154 segment, using an X (flexion/extension), Y (medial/lateral), Z (axial) Cardan sequence as
155 previously employed within golf research to measure wrist mechanics (Joyce, Burnett,
156 Cochrane, & Reyes, 2016; Sinclair, Currigan, Fewtrell, & Taylor, 2014), and is an equivalent
157 Cardan sequence recommended by (Wu et al., 2005). Movement in extension, radial
158 deviation and external rotation were defined as positive and flexion, ulnar deviation and
159 internal rotation were defined as negative. The club head was defined proximally using the
160 two superior markers on the clubface, with the marker closest to the shaft as the medial and
161 the other as lateral; inferior clubface markers were used to define the clubface distally, again
162 with the marker closest to the shaft as the medial and that furthest away as lateral. To
163 ascertain the clubface angle at impact, the club head angle was referenced in the z -axis of the
164 cross segment on the mat (positive values depicting a clubface pointing left of the ball-to-
165 target line and negative values to the right of the ball-to-target line), in addition club head
166 velocity was calculated at impact. Data were filtered using a low-pass Butterworth filter with
167 a cut off frequency of 25 Hz.

168 Four events were identified and used to divide the swing into three phases, with the
169 time between each event normalised to 101 points. “Onset” was defined when the club head
170 linear speed crossed a threshold value of 0.0 m/s in the global x -axis on swing ascent. “Top”
171 was defined when the club head linear speed reached its lowest negative value in the global z -
172 axis prior to swing decent. “Impact” was defined immediately before the ball recorded a

173 positive velocity. Finally, “Follow through” was defined when the left hand linear speed
174 crossed a threshold of 0.0 m/s in the global x -axis following the impact event.

175 **Statistical Analysis**

176 Data were analysed using SPSS Statistics 23.0 (IBM Corporation, USA) software.
177 Repeated measures ANOVAs were used to test for differences between wrist joint angles at
178 the swing onset, top and impact events, maximum and minimum angles, ROM and clubface
179 angle and velocity at impact. Main effects were assessed using the Greenhouse–Geisser
180 correction when Mauchly’s sphericity test was violated and effect sizes were provided
181 through the partial eta-squared (η_p^2) statistic. Post hoc pairwise comparisons were made
182 using the Bonferroni test when appropriate. A P -value < 0.05 was considered as significant
183 for all statistical tests.

184 **Results**

185 Golf swing wrist kinematics (means and standard deviations) for all grip types are
186 shown in Table 1. The following details any significant findings.

187 **Joint Angles at Identified Events**

188 **Onset.** While it could not be predetermined based on previous empirical study
189 exactly how the wrist joint would differ, it was important to test for at least some level of
190 change to support the visual manipulation checks employed. For the left wrist, there were
191 main effects with large effect sizes for grip type on flexion/extension, $P < 0.001$, $\eta_p^2 = 0.78$,
192 and internal/external rotation, $P < 0.001$, $\eta_p^2 = 0.73$, angles, with significant differences
193 evident in flexion/extension between neutral and weak ($P = 0.001$), neutral and strong ($P =$
194 0.002) and strong and weak ($P < 0.001$) grips and for internal/external rotation between
195 neutral and weak ($P < 0.001$), neutral and strong ($P = 0.029$) and strong and weak ($P < 0.001$)
196 grips. Similarly for the right wrist, main effects with large effect sizes for grip type were
197 revealed in flexion/extension, $P < 0.001$, $\eta_p^2 = 0.78$ and internal rotation, $P < 0.001$, $\eta_p^2 =$

198 0.73, but also ulnar/radial deviation with a medium effect size, $P = 0.018$, $\eta_p^2 = 0.37$. Post
199 hoc analyses revealed significant differences in flexion/extension between neutral and weak
200 ($P = 0.003$), neutral and strong ($P < 0.001$), and strong and weak ($P < 0.001$) grips, in
201 internal/external rotation between neutral and weak ($P = 0.001$) and strong and weak ($P <$
202 0.001) grips, with neutral and strong closely approaching significance ($P = 0.055$). No
203 significant differences were found in right wrist ulnar/radial deviation although the
204 differences between neutral and weak ($P = 0.088$) and weak and strong ($P = 0.061$) showed a
205 trend towards significance.

206 **Top.** Data at the top of the swing reveal that onset differences were not always
207 consistent. For the left wrist, there were significant main effects with a large effect size for
208 grip type on flexion/extension, $P < 0.001$, $\eta_p^2 = 0.70$, and a medium effect size for
209 internal/external rotation, $P = 0.008$, $\eta_p^2 = 0.35$, angles. Significant differences were shown
210 in flexion/extension between neutral and strong ($P < 0.001$) and weak and strong ($P = 0.001$)
211 grips, with neutral and weak grips only approaching significance ($P = 0.07$), and for
212 internal/external rotation between strong and weak grips ($P = 0.036$). Right wrist kinematics
213 showed main effects with a large effect size for grip type on flexion/extension, $P = 0.002$, η_p^2
214 $= 0.43$, and medium effect sizes for ulnar/radial deviation, $P = 0.022$, $\eta_p^2 = 0.37$, and internal
215 rotation, $P = 0.03$, $\eta_p^2 = 0.27$. Post hoc tests revealed significant differences in
216 flexion/extension between weak and strong ($P = 0.005$) grips and in ulnar/radial deviation
217 between neutral and strong ($P = 0.02$) and weak and strong ($P = 0.045$) grips. No significant
218 differences between grips were shown for internal/rotation angles.

219 **Impact.** There were significant main effects with large effect sizes for left wrist grip
220 type on flexion/extension, $P = 0.002$, $\eta_p^2 = 0.57$, and internal/external rotation, $P = 0.003$, η_p^2
221 $= 0.49$, angles. Significant differences were shown in flexion/extension between neutral and
222 strong ($P = 0.019$), neutral and weak ($P = 0.011$) and weak and strong ($P = 0.006$) grips, and

223 for internal/external rotation between neutral and strong ($P = 0.029$) and strong and weak (P
224 $= 0.014$) grips. Right wrist kinematics showed main effects with large effect sizes for grip
225 type on flexion/extension, $F(2,22) = 8.98$, $P = 0.001$, $\eta_p^2 = 0.45$, ulnar/radial deviation, $P =$
226 0.002 , $\eta_p^2 = 0.43$, and a medium effect size for internal rotation, $P = 0.004$, $\eta_p^2 = 0.39$. Post
227 hoc analyses revealed significant differences between weak and strong grips in
228 flexion/extension ($P = 0.001$), ulnar/radial deviation ($P = 0.02$) and internal/external rotation
229 ($P = 0.012$) grips.

230 **Minimum/Maximum Angles and Range of Motion**

231 When analysing the entire golf swings from the onset to follow-through events, there
232 was a significant main effect with large effect size of grip type on left wrist minimum
233 flexion/extension, $P = 0.001$, $\eta_p^2 = 0.64$, and medium effect size for internal/external rotation,
234 $P = 0.009$, $\eta_p^2 = 0.35$, angles. Post hoc tests showed significant differences within
235 flexion/extension between neutral and strong ($P < 0.001$) and strong and weak ($P = 0.002$)
236 grips and within internal/external rotation there was a trend towards significance between
237 neutral and strong ($P = 0.068$) and strong and weak ($P = 0.057$) grips. There was a
238 significant main effect with a medium effect size of grip type on right wrist minimum
239 internal/external rotation angle, $P = 0.027$, $\eta_p^2 = 0.34$, but post hoc tests showed no
240 significant differences between each of the grips. Right wrist minimum ulnar/radial deviation
241 only tended towards significance, $P = 0.051$. There was a significant main effect with
242 medium effect size of grip type on left wrist maximum flexion/extension, $P = 0.002$, $\eta_p^2 =$
243 0.34 . Post hoc tests showed significant differences between neutral and strong ($P = 0.012$).
244 There was a significant main effect with large effect size of grip type on right wrist maximum
245 flexion/extension angle, $P = 0.007$, $\eta_p^2 = 0.43$. Right wrist maximum internal/external
246 rotation approached significance, $P = 0.064$. Post hoc tests revealed significant differences
247 for flexion/extension between strong and weak ($P = 0.016$), with neutral and strong grips

248 almost reaching significance ($P = 0.05$). Despite these differences in minimum and
249 maximum angles, overall ROM appeared to be relatively unaffected. There was only a
250 significant main effect with medium effect size of grip type on left wrist flexion/extension
251 ROM, $P = .045$, $\eta_p^2 = 0.29$. However, post hoc analyses revealed nonsignificant results.

252

253 ***Table 1 here***

254

255 **Club Kinematics at Impact**

256 There was a significant main effect with a large effect size of grip type on clubface
257 angle, $P = 0.001$, $\eta_p^2 = 0.47$. As expected, the neutral grip clubface angle was between the
258 angles for strong and weak grips. Notably, all clubfaces were presented to the same side
259 relative to the ball–target line, to the right (Table 2). Significant differences, however, were
260 only found between neutral and weak ($P = 0.019$) and strong and weak ($P = 0.011$) grips.
261 There was no significant main effect found for grip type on club head velocity, $P = 0.301$.

262

263 ***Table 2 here***

264

265 **Discussion**

266 This study addressed methodological shortcomings of previous research into golf
267 wrist mechanics by employing a three-dimensional analysis using anatomical LCSs.
268 Furthermore, it compared several club head kinematics at impact resulting from purposeful,
269 albeit acute, modifications to grip type within a sample of high-level golfers. Wrist
270 movement was tri-planar in nature, indicating greater complexity than previously reported
271 (Cahalan et al., 1991; Fedorcik et al., 2012; Zheng et al., 2008). While this method is not
272 always appropriate for golf swing analyses (e.g., when analysing general timing), it is

273 important to recognise that simplistic wrist analyses could ignore important movement
274 patterns.

275 Regarding internal/external rotation, mean trail wrist ROM was similar to previous
276 data (Gilmour et al., 2012; Gupta & Moosawi, 2005). Lead wrist mean ROM, however, was
277 much higher. Internal rotation was similar between wrists, indicating that additional external
278 rotation accounted for this difference. Considering the lead wrist's injury prevalence in high-
279 level golfers, this subtle difference could be a contributing factor. Moreover, from the
280 address position the lead wrist was closest to its maximum internal rotation angle, which is
281 also likely to persist for the longest duration as the golfer sets up and prepares to execute the
282 shot. Although currently speculative in nature, the tri-planar data certainly appears able to
283 provide additional detail to begin exploring specific questions about golf swing technique and
284 the underlying causes of performance. Similarly, researchers exploring the 'X-factor'
285 principle have recently advocated the necessity for an anatomical LCS to gain a greater
286 biomechanical meaning (Brown, Selbie, & Wallace, 2013). Other factors that might interact
287 with this wrist movement to result in injury include the nature of club-ground contact and
288 intensity of practice undertaken. At present, however, we await further investigations along
289 these lines.

290 Looking beyond the novel internal/external rotation data, the nonsignificant
291 differences in club head velocity suggests that any differential in observed shot distance
292 between grip types may not be due to the transfer of energy to the club head. Instead,
293 underpinning causes could reside with precision elements; for instance, clubface loft, angle in
294 relation to the swing direction and, therefore, resultant ball trajectory. Further support for
295 this can be inferred from the trail wrist flexion/extension ROM during the downswing—
296 which is indicative of angular velocity and directly related to the amount of power applied
297 (Sinclair et al., 2014)—showing very little/no change across the three grip conditions.

298 Differences between the tri-planar angles were however evident at impact. As such, it is
299 possible that the type rather than the amount of movement needs further consideration when
300 examining the golf swing ‘release’ principle (Najar, 2010). From these data and for this
301 sample at least, simply changing the grip position does not appear beneficial to increasing
302 club head velocity.

303 Top of the backswing data are also of interest. Specifically, the mean lead wrist was
304 in extension irrespective of grip type and all club face angles were aligned to the right of the
305 shot direction line (open) at impact. Notably, this is somewhat contrary to Haney’s (2012)
306 explanation that the wrist angle at the top of the backswing, and subsequent impact
307 orientation, could relate to grip. As a possible interpretation, these high-level golfers were
308 able to resist the ‘likelihood’ of closing the clubface at impact with a strong grip, maintaining
309 a relatively square position, whereas this was comparatively more challenging with a weak
310 grip. This supports PGA’s (2010) suggestion that golfers tend closer towards a strong rather
311 than weak grip. Indeed, most participants expressed a preference for either a neutral or
312 strong grip during debriefs that followed the trials. It is perhaps, therefore, unsurprising that
313 the strong grip could be more functionally adapted compared to the weak grip, due to
314 increased familiarity and comfort in the executions.

315 Moreover, regarding individual differences, despite Table 1 showing strong–neutral–
316 weak grips resulted in a fairly consistent and ordered ascending/descending sequence of
317 angles for the variables, some showed no difference across conditions. Notably, upon
318 inspection of individual data, no single participant entirely matched these ordered sequences
319 from the group data. As such, this supports the rationale for individual technical analyses
320 within coaching practice (Brown et al., 2011; Kostrubiec, Zanone, Fuchs, & Kelso, 2012).
321 Undoubtedly, some movements will be similar across participants, therefore abiding by a
322 general technical template. However, coaches should be cautious when constructing

323 individualised mental models of performance not to fall into the ‘flaw of average’ heuristic
324 trap (Rose, 2016) when assessing many swing variables. In short, the idea that a mental
325 model of performance should target the average of skilled/elite players (e.g., Mann & Griffin,
326 1998), even if ‘windows’ around the mean are catered for (Rose, 2016), is inevitably
327 suboptimal at best.

328 In addition to an improved understanding of mechanics by employing LCSs, there are
329 also pragmatic advantages to be realised. Specifically, this arises when requiring longitudinal
330 analyses, such as when diagnosing and monitoring technique during skill refinement (Carson
331 & Collins, 2011). Using more commonly employed global co-ordinate systems in the lab and
332 applied settings (e.g., a fixed camera positioned in the sagittal or coronal plane) cannot
333 guarantee the exact relative positioning between the golfer and co-ordinate system axes
334 between sessions. Consequently, intersession comparisons are less reliable and have greater
335 planar cross-talk, with LCSs suffering fewer inconsistencies in measurement; data are less
336 affected by variations across trials, days and environments.

337 Despite methods employed in this study, limitations must be recognised. Technique
338 variations have been reported across different golf clubs (Egret, Vincent, Weber, Dujardin, &
339 Chollet, 2003), especially when executing from the ground and not a tee. Further
340 understanding would therefore derive from employing LCSs beyond the sole use of a driver.
341 From a motor control perspective, issues of ecological validity are also noteworthy in that the
342 laboratory environment is unrepresentative of golf course conditions (Pinder, Davids,
343 Renshaw, & Araújo, 2011). It has been reported that changes in automaticity can occur
344 following the removal of naturalistic features (Carson, Collins, & Richards, 2016), however
345 we cannot say in this case whether kinematics were compromised in any way. Mobile
346 technologies that permit motion capture on the golf course may be able to overcome this
347 limitation in future investigations. Relatedly, when considering participants’ high skill status,

348 two of the grip conditions were less familiar/comfortable and therefore reflect a short-term
349 perturbation to technique which we would expect to be disruptive of control processes
350 (Charlton & Starkey, 2011). Accordingly, we recommend caution in assuming that any
351 differences truly represent well-established techniques. Future research may extend this
352 novel methodology by testing between individuals with different preferable grip types and
353 collecting valuable ball flight data to enhance our understanding of the relationship with
354 performance outcomes. Finally, addressing the collection and processing of kinematic data,
355 this study defined the hand as a rigid segment and was able to detect differences within that
356 segment relative to the forearm, however a more detailed analysis of the structures within the
357 hand maybe possible (Gupta & Moosawi, 2005), which may yield a greater understanding of
358 the movement and injury risks during the golf swing. Additionally, while Joyce, Burnett, and
359 Ball (2010) determined that different joint angles for the trunk resulted from different Cardan
360 sequences, it is important to highlight that no research has yet investigated any such
361 differences when assessing wrist motion.

362 **Conclusion**

363 This paper extends current knowledge relating to the lead and trail wrist mechanics
364 during the golf swing, through use of anatomical LCSs. Specifically, its contribution can be
365 seen in the identification of movement in internal/external rotation and the interpretation of
366 data from a coaching perspective. It is hoped that the methods employed in this study can be
367 used to inform future research into many aspects of skill, technique analysis and skill
368 development, and provided a greater understanding of injury mechanisms and their
369 prevention.

370

371 **Disclosure Statement**

372 There is no potential conflict of interest concerning this non-funded research.

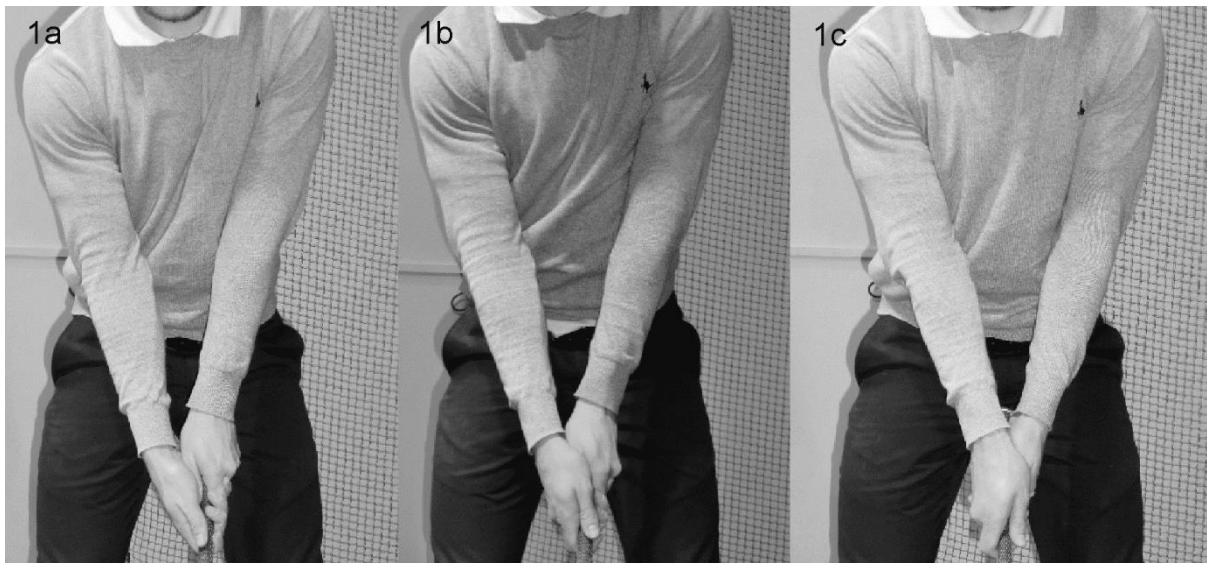
References

- 1
2 Barclay, C., West, S., Shoaib, Q., Morrissey, D., & Langdown, B. (2011). Injuries patterns
3 among professional golfers: An international survey. *British Journal of Sports*
4 *Medicine, 45*, e1. doi:10.1136/bjism.2010.081554.12
- 5 Brown, S. J., Nevill, A. M., Monk, S. A., Otto, S. R., Selbie, W. S., & Wallace, E. S. (2011).
6 Determination of the swing technique characteristics and performance outcome
7 relationship in golf driving for low handicap female golfers. *Journal of Sports*
8 *Sciences, 29*, 1483–1491. doi:10.1080/02640414.2011.605161
- 9 Brown, S. J., Selbie, W. S., & Wallace, E. S. (2013). The X-Factor: An evaluation of
10 common methods used to analyse major inter-segment kinematics during the golf
11 swing. *Journal of Sports Sciences, 31*, 1156–1163.
12 doi:10.1080/02640414.2013.775474
- 13 Cahalan, T. D., Cooney III, W. P., Tamai, K., & Chao, E. Y. S. (1991). Biomechanics of the
14 golf swing in players with pathologic conditions of the forearm, wrist, and hand. *The*
15 *American Journal of Sports Medicine, 19*, 288–293.
16 doi:10.1177/036354659101900314
- 17 Carson, H. J., & Collins, D. (2011). Refining and regaining skills in fixation/diversification
18 stage performers: The Five-A Model. *International Review of Sport and Exercise*
19 *Psychology, 4*, 146–167. doi:10.1080/1750984x.2011.613682
- 20 Carson, H. J., & Collins, D. (2016). The fourth dimension: A motoric perspective on the
21 anxiety–performance relationship. *International Review of Sport and Exercise*
22 *Psychology, 9*, 1–21. doi:10.1080/1750984X.2015.1072231
- 23 Carson, H. J., Collins, D., & Richards, J. (2016). Initiating technical refinements in high-level
24 golfers: Evidence for contradictory procedures. *European Journal of Sport Science,*
25 *16*, 473–482. doi:10.1080/17461391.2015.1092586

- 26 Charlton, S. G., & Starkey, N. J. (2011). Driving without awareness: The effects of practice
27 and automaticity on attention and driving. *Transportation Research part F: Traffic*
28 *Psychology and Behaviour, 14*, 456–471. doi:10.1016/j.trf.2011.04.010
- 29 Egret, C. I., Vincent, O., Weber, J., Dujardin, F. H., & Chollet, D. (2003). Analysis of 3D
30 kinematics concerning three different clubs in golf swing. *International Journal of*
31 *Sports Medicine, 24*, 465–470. doi:10.1055/s-2003-41175
- 32 Fedorcik, G. G., Queen, R. M., Abbey, A. N., Moorman Iii, C. T., & Ruch, D. S. (2012).
33 Differences in wrist mechanics during the golf swing based on golf handicap. *Journal*
34 *of Science and Medicine in Sport, 15*, 250–254. doi:10.1016/j.jsams.2011.10.006
- 35 Gilmour, A., Richards, J., & Redfern, D. R. M. (2012). Investigation of 3D planar wrist
36 movements during activities of daily living. *Journal of Bone & Joint Surgery, British*
37 *Volume, 94-B*, 65
- 38 Gupta, A., & Moosawi, N. A. (2005). How much can carpus rotate axially? An in vivo study.
39 *Clinical Biomechanics, 20*, 172–176. doi:10.1016/j.clinbiomech.2004.09.014
- 40 Haney, H. (2012, 4 June). Check your left wrist. *Golf Digest*. Retrieved from
41 <http://www.golfdigest.com/story/hank-haney-left-wrist>
- 42 Joyce, C., Burnett, A., & Ball, K. (2010). Methodological considerations for the 3D
43 measurement of the X-factor and lower trunk movement in golf. *Sports*
44 *Biomechanics, 9*, 206–221
- 45 Joyce, C., Burnett, A., Cochrane, J., & Reyes, A. (2016). A preliminary investigation of trunk
46 and wrist kinematics when using drivers with different shaft properties. *Sports*
47 *Biomechanics, 15*, 61–75. doi:10.1080/14763141.2015.1123764
- 48 Kostrubiec, V., Zanone, P.-G., Fuchs, A., & Kelso, J. A. S. (2012). Beyond the blank slate:
49 Routes to learning new coordination patterns depend on the intrinsic dynamics of the

- 50 learner—experimental evidence and theoretical model. *Frontiers in Human*
51 *Neuroscience*, 6, 1–14. doi:10.3389/fnhum.2012.00222
- 52 Lindsay, D., Mantrop, S., & Vandervoort, A. (2008). A review of biomechanical differences
53 between golfers of varied skill levels. *International Journal of Sports Science and*
54 *Coaching*, 3(Supplement 1), 187–197. doi:10.1260/174795408785024117
- 55 MacKenzie, S. J., & Sprigings, E. J. (2009). A three-dimensional forward dynamics model of
56 the golf swing. *Sports Engineering*, 11, 165–175. doi:10.1007/s12283-009-0020-9
- 57 Mann, R., & Griffin, F. (1998). *Swing like a pro: The breakthrough scientific method of*
58 *perfecting your golf swing*. New York: Broadway Books.
- 59 McCarroll, J. R., Retting, A. C., & Shelbourne, K. D. (1990). Injuries in the amateur golfer.
60 *The Physician and Sports Medicine*, 18, 122-126
- 61 Najar, B. (2010, 11 November). Get a grip - The right grip for you. Retrieved from
62 [http://www.pga.com/golf-instruction/instruction-feature/fundamentals/get-grip-right-](http://www.pga.com/golf-instruction/instruction-feature/fundamentals/get-grip-right-grip)
63 [grip](http://www.pga.com/golf-instruction/instruction-feature/fundamentals/get-grip-right-grip)
- 64 Nesbit, S. M. (2005). A three dimensional kinematic and kinetic study of the golf swing.
65 *Journal of Sports Science and Medicine*, 4, 499–519
- 66 PGA. (2008). *Study guide: Golf coaching I*. United Kingdom: The Professional Golfers’
67 Association.
- 68 PGA. (2010). *Study guide: Introduction to golf coaching*. Sutton Coldfield: The Professional
69 Golfers’ Association of Great Britain and Ireland.
- 70 Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Representative learning design
71 and functionality of research and practice in sport. *Journal of Sport and Exercise*
72 *Psychology*, 33, 146–155. doi:10.1123/jsep.33.1.146
- 73 Rose, T. (2016). *The end of average: How we succeed in a world that values sameness*.
74 Canada: HarperCollins.

- 75 Sharp, R. S. (2009). On the mechanics of the golf swing. *Proceedings of The Royal Society A*,
76 465, 551-570. doi:10.1098/rspa.2008.0304
- 77 Sinclair, J., Currigan, G., Fewtrell, D. J., & Taylor, P. J. (2014). Biomechanical correlates of
78 club-head velocity during the golf swing. *International Journal of Performance*
79 *Analysis in Sport*, 14, 54–63
- 80 Sprigings, E. J., & Neal, R. J. (2000). An insight into the importance of wrist torque in
81 driving the golfball: A simulation study. *Journal of Applied Biomechanics*, 16, 356–
82 366. doi:10.1123/jab.16.4.356
- 83 Wu, G., van der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., . . .
84 Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems
85 of various joints for the reporting of human joint motion—Part II: Shoulder, elbow,
86 wrist and hand. *Journal of Biomechanics*, 38, 981–992.
87 doi:10.1016/j.jbiomech.2004.05.042
- 88 Zheng, N., Barrentine, S. W., Fleisig, G. S., & Andrews, J. R. (2008). Kinematic analysis of
89 swing in pro and amateur golfers. *International Journal of Sports Medicine*, 29, 487–
90 493. doi:10.1055/s-2007-989229
- 91

92 **Figures**

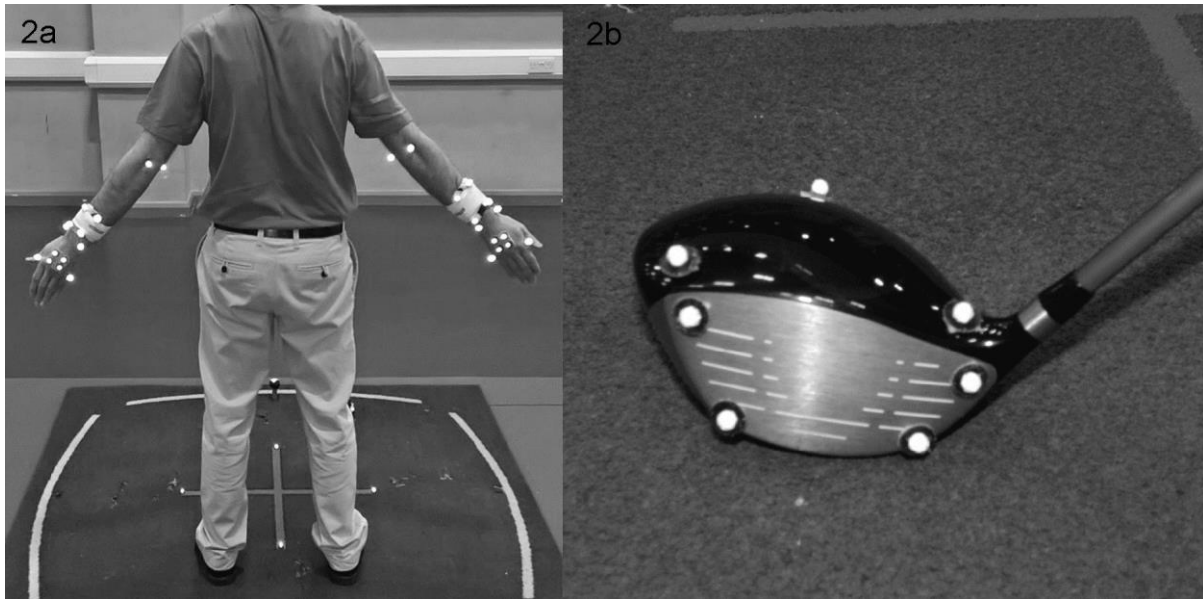
93

94 *Figure 1.* Different address grip positions viewed in the global coronal plane for a right-
95 handed golfer. The strong grip (1a) is characterised by the lead hand being positioned on top
96 of the handle with three knuckles shown to the golfer (first person perspective) and the trail
97 hand wrapped underneath with one knuckle shown. The neutral grip (1b) presents the golfer
98 with a view of two knuckles on each hand and the weak grip (1c) showing three knuckles on
99 the trail hand and one on the lead.

100

101

102



103

104 *Figure 2.* Anatomical and cluster marker placements on the forearm and hand segments, ball

105 marker and floor markers (2a). Club head and clubface marker placements (2b).

106 Table 1. *Lead and Trail Wrist Kinematics*

	Left (Lead) Wrist			Right (Trail) Wrist		
	Strong	Neutral	Weak	Strong	Neutral	Weak
Swing Onset (°)						
Flexion/Extension	33.8 ± 10.0 ^{*,**}	29 ± 10.9 ^{*,***}	22.2 ± 10.1 ^{**,***}	-2.2 ± 4.7 ^{**,***}	3.8 ± 5.4 ^{*,**}	11.4 ± 6.0 ^{*,***}
Ulnar/Radial Deviation	-15.2 ± 11.7	-15.0 ± 11.1	-15.8 ± 10.7	-22.6 ± 8.8	-23.6 ± 8.9	-24.7 ± 8.8
Internal/External Rotation	-33.7 ± 6.1 ^{**,***}	-29.9 ± 6.3 ^{*,**}	-24.6 ± 5.3 ^{*,***}	-13.0 ± 7.4 ^{**}	-16.9 ± 7.2 [*]	-23.1 ± 8.1 ^{*,**}
Top (°)						
Flexion/Extension	14.4 ± 12.1 ^{*,**}	6.6 ± 11.8 [*]	1.7 ± 10.6 ^{**}	51.9 ± 10.2 [*]	54.0 ± 11.3	57.6 ± 9.1 [*]
Ulnar/Radial Deviation	26.3 ± 14.3	24.3 ± 12.6	22.4 ± 11.9	26.4 ± 6.2 ^{*,**}	24.8 ± 6.5 [*]	21.5 ± 9.2 ^{**}
Internal/External Rotation	-22.2 ± 10.3 [*]	-23.6 ± 9.2	-24.7 ± 10.4 [*]	-8.6 ± 10.0	-10.1 ± 10.0	-12.2 ± 10.0
Impact (°)						
Flexion/Extension	8.9 ± 10.5 ^{*,***}	5.5 ± 12.5 ^{*,**}	3.0 ± 13.0 ^{**,***}	19.9 ± 6.5 [*]	21.3 ± 6.9	23.2 ± 6.4 [*]
Ulnar/Radial Deviation	-24.2 ± 7.7	-24.6 ± 8.7	-25.3 ± 9.3	-22.7 ± 9.3 [*]	-24.1 ± 9.9	-25.7 ± 11.0 [*]
Internal/External Rotation	-24.2 ± 7.0 ^{*,**}	-21.4 ± 7.1 [*]	-19.0 ± 8.5 ^{**}	-16.2 ± 8.9 [*]	-18.0 ± 9.1	-21.1 ± 6.8 [*]
ROM (°)						
Flexion/Extension	59.76 ± 14.3	61.65 ± 13.2	64.11 ± 12.9	76.85 ± 11.2	77.85 ± 10.2	78.56 ± 9.9
Ulnar/Radial Deviation	63.82 ± 9.9	63.36 ± 10.0	63.27 ± 11.5	72.73 ± 7.5	73.27 ± 8.0	72.97 ± 7.7
Internal/External Rotation	45.77 ± 9.6	45.20 ± 7.4	44.5 ± 8.7	32.95 ± 11.7	32.01 ± 11.3	33.53 ± 12.2

Minimum Angle (°)						
Flexion/Extension	$-3.58 \pm 9.8^{*,**}$	$-8.24 \pm 9.3^*$	$-11.56 \pm 7.4^{**}$	-18.19 ± 9.3	-17.43 ± 9.4	-15.33 ± 9.9
Ulnar/Radial Deviation	-29.03 ± 8.2	-28.70 ± 8.0	-28.80 ± 8.1	-38.0 ± 7.7	-38.70 ± 7.3	-39.01 ± 7.5
Internal/External Rotation	-39.02 ± 8.8	-37.21 ± 8.6	-36.47 ± 8.7	-30.57 ± 6.1	-30.58 ± 6.0	-33.78 ± 5.5
Maximum Angle (°)						
Flexion/Extension	$56.18 \pm 10.2^*$	$53.40 \pm 10.4^*$	52.60 ± 11.2	$58.66 \pm 11.2^*$	60.42 ± 10.7	$63.22 \pm 9.6^*$
Ulnar/Radial Deviation	34.80 ± 12.8	34.66 ± 12.1	34.48 ± 12.8	34.74 ± 7.0	34.57 ± 8.0	33.96 ± 7.5
Internal/External Rotation	6.76 ± 6.9	7.98 ± 6.7	8.03 ± 8.3	2.38 ± 10.3	1.42 ± 10.9	-0.24 ± 10.9

107

108 Table 2. *Club Head Kinematics at Impact*

	Grip Type		
	Strong	Neutral	Weak
Angle (°)	$-1.51 \pm 4.7^{**}$	$-2.57 \pm 4.5^*$	$-6.36 \pm 6.9^{*,**}$
Velocity (m/s)	38.2 ± 3.6	38.6 ± 4.0	38.0 ± 3.4

109 *, ** indicates significant differences, $P < 0.05$, of pairwise comparisons