Prediction and Visualisation of Bony Impingement for Subject Specific Total Hip Arthroplasty *

A. Palit, R. King, Y. Gu, J. Pierrepont, Z. Hart, M. T. Elliott, M. A. Williams

Abstract— **Bony impingement (BI) may contribute to restricted hip joint motion, and recurrent dislocation after total hip arthroplasty (THA), and therefore, should be avoided where possible. However, BI risk assessment is generally performed intra-operatively by surgeons, which is partially subjective and qualitative. Therefore, the aim of the study was to develop a method for identifying subject-specific BI, and subsequently, visualising BI area on native bone anatomy to highlight the amount of bone should be resected. Activity definitions and subject-specific bone geometries, constructed from CT scans, with planned implants were used as inputs for the method. For each activity, a conical clearance angle (CCA) was checked between femur and pelvis through simulation. Simultaneously, BI boundary and area were automatically calculated using ray intersection and region growing algorithm respectively. The potential use of the developed method was explained through a case study using an anonymised pre-THA patient data. Two pure (flexion, and extension) and two combined hip joint motions (internal and external rotation at flexion and extension respectively) were considered as activities. BI area were represented in two ways: (a) CCA specific where BI area for each activity with different CCAs was highlighted, (b) activity specific where BI area for all activities with a particular CCA was presented. Result showed that BI area between the femoral and pelvic parts was clearly identified so that the pre-operative surgical plan could be adjusted to minimise impingement. Therefore, this method could potentially be used to examine the effect of different pre-operative plans and hip motion on BI, and to guide bony resection during THA surgery.**

I. INTRODUCTION

Total hip arthroplasty (THA) is regarded as one of the most effective surgical intervention to relieve pain and restore lost mobility to patients with severe hip osteoarthritis. However, there are many complications associated with post-THA such as limping, ongoing pain, dislocation, implant loosening, excessive wear of the prosthetic joint surfaces, fracture etc.[1]. Dislocation is one of the most serious complications amongst them and ranks in second position after aseptic loosening [2, 3]. It was reported that 90% of dislocation cases had evidence of impingement [4]. The impingement can occur between bony geometries, prosthetic implants, and/or soft tissue structures. Based on the type of impingement, Bartz et al. [4] classified dislocation mechanisms into three categories as follows: (a) prosthetic impingement (PI) which is the impingement between prosthetic femoral neck and the liner/cup, (b) bony impingement (BI) which occurs between the osseous femur and the osseous pelvis, and (c) spontaneous dislocation. Although the reason for spontaneous dislocation is not fully recognized, it is presumed that muscle weakness, soft tissue imbalance, or/and contracture of the hip joint could be the potential causes [3]. On the other hand, prosthetic impingement is associated with implants with a known set of variables such as position and orientation of acetabular and femoral implants, and implants design. These known variables allow the use of a computer simulation model to find optimal position and orientation of the acetabular and femoral implant or to find optimal design such as larger size of femoral head to reduce the prosthetic impingement [5]. BI, on the other hand, varies considerably amongst patients, and it depends on bone morphology around the hip [3]. It occurs due to anomalous contact between the greater and lesser trochanter, femoral neck and the anterior inferior iliac spine, acetabular margin, ilium, or ischium. In order to avoid bony impingement after THA, it is generally recommended to resect the osteophytes and bony prominence completely during the surgery or to increase the stem offset while positioning implants [6]. However, evaluation of risk of BI is mostly carried out intra-operatively by the surgeon. Therefore, it is partially subjective and entirely qualitative in nature. As a consequence, despite using recommended implant positions and resecting the osteophytes and bony prominence, complications arises after THA, especially in patients with larger bony prominence

Therefore, the aim of the paper was to develop a method for identifying subject-specific BI, and subsequently, visualise the impingement area on bone anatomy. This method could potentially be used to examine the effect of different pre-operative plans and hip motion on BI. This novel visualisation representation could guide surgeons to decide how much and from where the bony areas should be resected during THA to avoid BI for a particular stem offset, or even find the effect of different stem offset on BI for same activities of daily living.

The paper is organised as follows. The next section detailed an overview of the proposed method to identify and visualise subject-specific BI area. A case study was then included to explain the potential use of the method. The rest of

* Research supported by Corin Group Ltd.

A. Palit, M. T. Elliott, M. A. Williams are with WMG, University of Warwick, CV4 7AL, UK, (A.Palit.1@warwick.ac.uk, M.T.Elliott@warwick.ac.uk, M.A.Williams.1@warwick.ac.uk).

R. King is with University Hospital Coventry and Warwickshire NHS Trust, Trauma & Orthopaedics, Coventry, UK (email: Richard.King@uhcw.nhs.uk).

Y. Gu, J. Pierrepont, are with Corin Group Pty Ltd, Pymble, Australia and School of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney, Sydney, Australia (e-mail: Yolanda.Gu@coringroup.com, Jim.Pierrepont@coringroup.com)

Z. Hart is with Corin Group Pty Ltd, Pymble, Australia (e-mail: Zoe.Hart@coringroup.com)

the paper described the results from the case study followed by discussion and conclusions.

II. Materials and Methods

A. Inputs

The inputs required for the method were broadly classified into two sub-categories (Fig. 1). Input Type-I was the bone geometries with prosthetic implants positioned onto it according to THA planning. Therefore, Input Type I was associated with surgical planning, and the following steps were carried out to achieve it: (a) CT scanning of a patient required THA surgery, (b) construction of bone geometries of the patient from CT scans, (c) identification of bony landmarks by experienced engineers/surgeons, (d) CAD model of planned implants to be used for THA, and (e) planned implant positioning (e.g. inclination and anteversion angle or stem offset etc.) onto the bone geometries. After all the aforementioned steps, the native bone geometry with planned implants, were used as Input Type I. In this work, STL file format with triangular mesh was used to represent implants and bone geometries. On the other hand, Input Type II dealt with the hip joint motion under consideration. This hip motion could be measured activities using gait analysis or IMU sensors, hypothetical activities such as pure joint motion (e.g. simple flexion, extension etc.). Using these inputs, the subject-specific BI area was identified, and highlighted as described in following sections (Fig. 1 and 2).

B. STEP 1: Generation of a conical hip joint motion and conical clearance angle (CCA)

The hip joint motion under consideration was discretized into (N_{Act}*+1)* number of postures (steps) including starting posture with step size Δt_{Act}. For example, flexion up to 90^0 could be discretized with $\Delta t_{Act} = 45^0$ *and* $N_{Act} + 1 = 3$ so that the femur flexion could be represented with three postures ($I_{pos} = 0^0$, 45^0, 90^0) starting from 0^0 (Fig. 2a). For each posture, a conical motion of femur was created with an aperture angle α and the axis of the cone was the femur axis at a particular posture during the hip joint motion under consideration. This conical motion of femur was then used to check whether there was any BI, and the aperture angle (α) of the conical motion was hypothesized as a conical clearance angle (CCA). The conical motion of femur with a particular CCA was discretized with N_{Cone} number of positions with a step size Δt_{Cone} where J_{pos} represented each position of femur during this conical motion with particular CAA (Fig. 1). Fig. 2b shows that the conical motion is discretized with N_{Cone} =8 static positions. The next step of the method was to check for impingement, and find the corresponding BI boundary if there was any impingement.

C. STEP 2: Identification of BI boundary

For each position of the conical motion, intersection between two geometrical structures i.e. femur and pelvis was calculated. Möller-Trumbore (MT) 'ray triangle intersection' (RTI) algorithm [7] was used to find the BI boundary between femur and pelvis (Fig. 2d and e). Intersection points between a pair of surfaces were identified by assuming that each edge of each constituent triangular mesh represented an infinitesimal ray. Therefore, the intersection points were found by solving the ray-triangle intersection problem using the Barycentric coordinate based solution presented by Möller and Trumbore [7]. In this work, Matlab function 'fastMesh2Mesh' developed by Thomas Seers was used for calculating the femur to pelvis intersections using MT algorithm mesh [8].

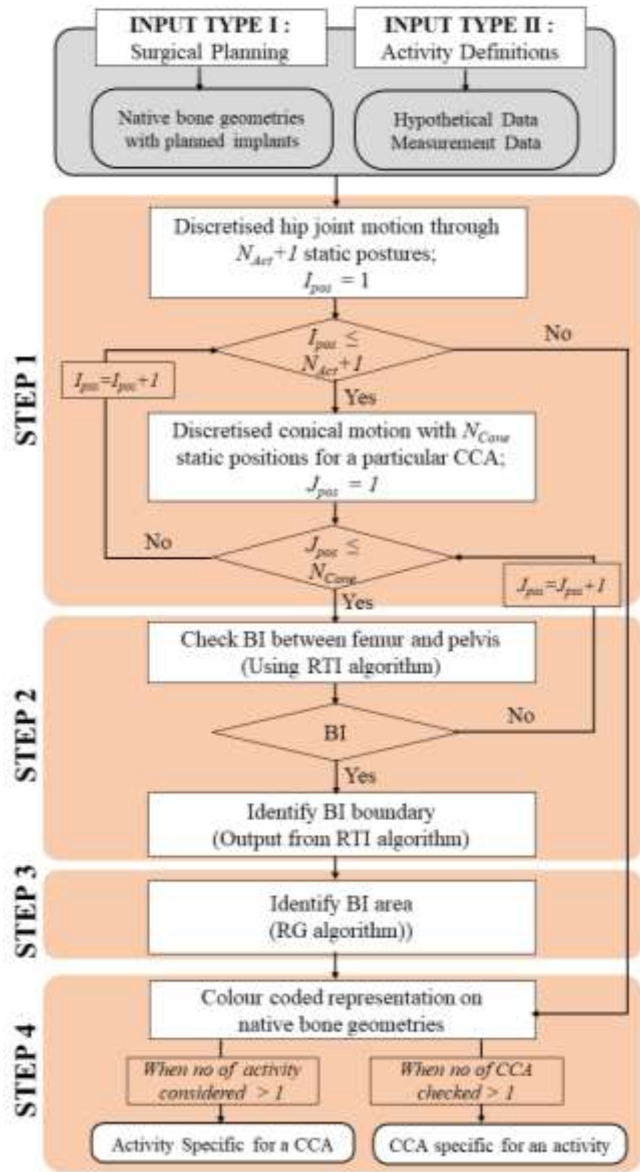

Figure 1: A brief overview of the proposed method along with the inputs and steps involved to identify and visualise subject-specific BI area. RTI - Ray Triangle Intersection, RG - Region Growing

D. STEP 3: Identification of BI area

If there was a BI during any particular time step of the conical movement, the boundary of the BI area for both pelvis and femur was identified in Step 3. In this step, a region growing algorithm (RGA) [9, 10] was used to automatically calculate the BI surface area, which is nothing but the triangular mesh element confined within this BI boundary (Fig. 2f). Therefore, the objective of the step was to find triangular face ids confined within the BI boundary.

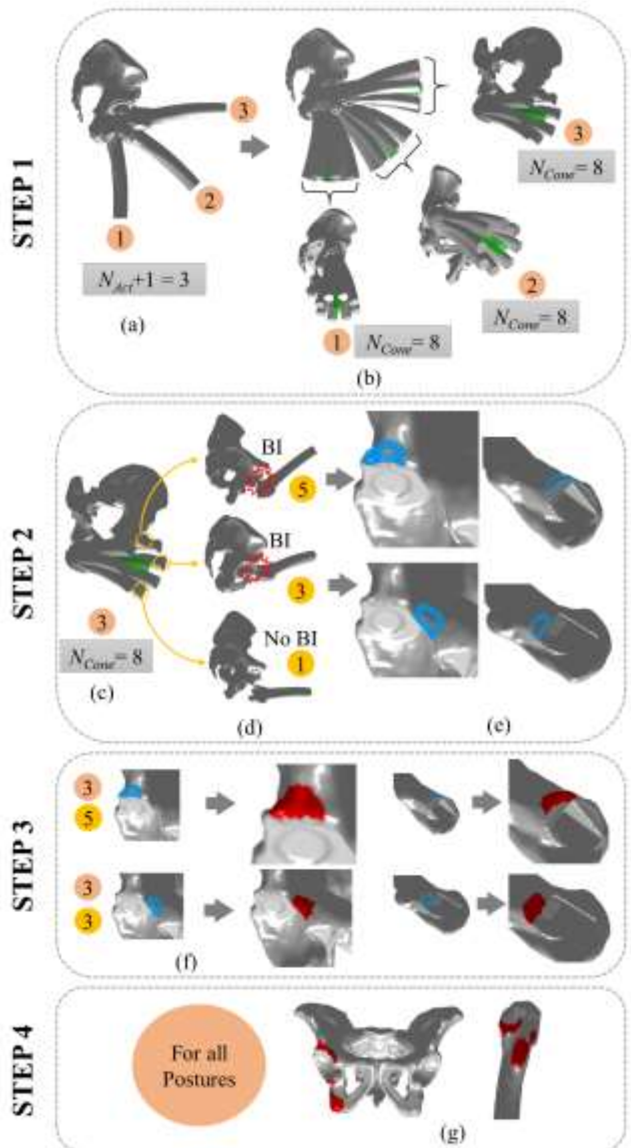

Figure 2: A brief overview of each step of the proposed method through an example of hip flexion of 90^0 from supine position.

The RGA was performed by proliferating the 'child' triangles around the 'seed' ones. A triangle was considered as a 'seed' triangle if all three of its vertices belonged to the same cluster. The RGA started with a random triangle which was considered as the first 'seed' triangle associated with first cluster. The RGA stopped when there was no 'seed' triangle available in the entire geometry, i.e. there was no new cluster to be created. On the other hand, a 'child' triangle around a 'seed' triangle was generated during the region growing operation if (a) the triangle was associated with same cluster, and (b) it had a common (sharing) edge i.e. two sharing vertices with an adjacent 'seed' triangle of same cluster. In the next step, the generated 'child' triangles were considered as 'seed' triangles of same cluster, and old 'seed' triangles ('seed triangles in the previous step) were considered as 'allocated' triangles within the same cluster. Subsequently, new 'child' triangles were detected around the new 'seed' triangles, and this process continued until there was no 'child' triangle (un-allocated triangles) available to be allocated within a same cluster. As a result, the region was grown around a 'seed' triangle confined within a closed boundary, and stopped automatically near to the edge of the boundary. The vertices of triangles at boundary edges were shared between two different clusters, and therefore, these triangles were not considered as 'seed' or 'child' triangle ('non-seeded' triangle). Finally, after applying RGA, the entire bone geometry (femur or pelvis) was clustered in two areas: (a) impinged areas, and (b) non-impinged areas. The triangular face ids of the impinged areas were recorded, and stored for future use (Fig. 2f).

As described above, the RGA was applied for each of the discretized conical motion step when there was BI (N_{Cone}^{BI} where $1 \le N_{Cone}^{BI} \le N_{Cone}$), and the triangular face ids of the triangular mesh for each of N_{Cone}^{BI} step were recorded. Therefore, after applying RGA for all N_{Cone}^{BI}, BI area on femur and pelvis were identified through triangular face ids for a particular CCA at a particular posture.

E. STEP 4: Representation of BI area

The BI area was identified using triangular face ids of the STL geometries for each of the discretized N_{Cone}^{BI} position at each of the $(N_{Act}+1)$ postures. At the end of all postures, all the BI face ids were grouped together and highlighted with a colour on the respective bone geometries. Fig. 2g shows the BI area due to all the postures (1, 2, and 3) which represented flexion of 90^0 from supine position. The entire process (STEP 1 to 4) could be carried out either for different activities with a particular CCA or for one activity with different CCA. Based on that, the BI area could be represented in two different ways (Fig 1) as follows. (a) CCA specific, where the effect of different CCA for a particular activity was highlighted through a CCA specific colour code. (b) Activity specific, where BI area due to different activities for a particular CCA was represented using an activity specific colour code. These two representations would provide the surgeons intuitive and suggestive information about the critical region of the bone that should be resected to avoid BI.

III. CASE STUDY

In order to highlight the potential use of the developed method, a case study of a patient that needed THA was considered. The anonymised data of the patient was provided by Corin Ltd, which was approved by the University of Warwick Biomedical & Scientific Research Ethics Committee (BSREC) (2012-03-710). The prosthetic implants positioned on to the native bone geometry according to the surgical plan was used as Input Type I as mentioned in the input section of the method. This was performed by a dedicated experienced engineer at Corin Ltd. Four hypothetical activities [11], which are generally performed during THA by surgeons, were used as Input Type II as follows: (a) extension of 10^0 from supine position, (b) flexion of 90^0 from supine position, (c) external rotation (ER) of 20^0 at 10^0 extension position, and (d) internal rotation (IR) of 30^0 at 90^0 flexion position. The first two activities were pure joint motions whereas the last two represented combined motions. Each activity was discretized with $(N_{Act} + 1) = 5$ number of postures. For each posture within an activity, three different CCA were used to check conical clearances as follows: (a) 5^0 , (b) 10^0 , and (c) 15^0 . The conical motion in each posture was discretized with $N_{Cone} = 10$ resolution.

IV. Results

A. CCA specific BI

Fig. 3 shows BI region for different CCA (5^0 , 10^0 , and 15^0) and for each of activities considered in the case study.

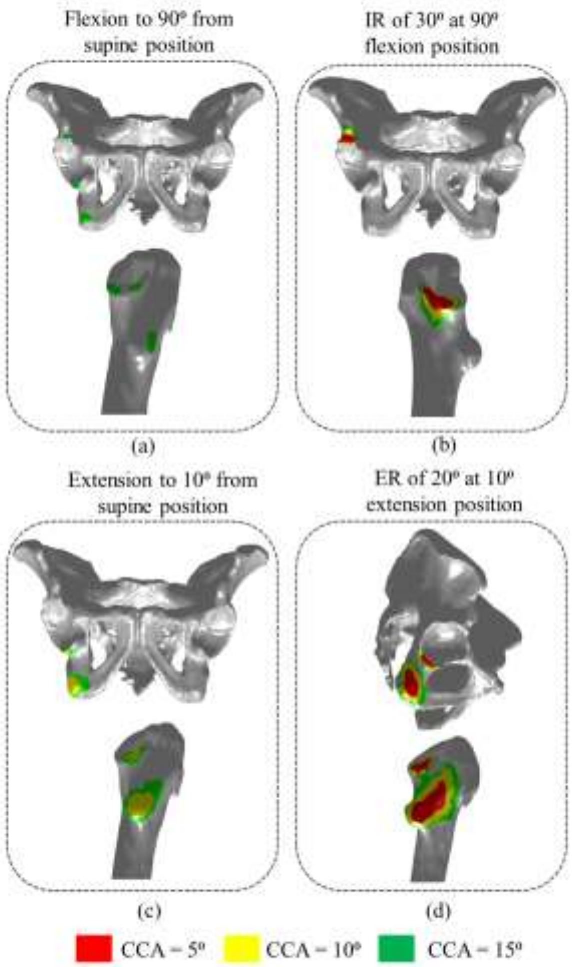

Figure 3: Colour coded representation of BI area for each activity considered in the case study – (a) flexion of 90^0 from supine position, (b) internal rotation of 30^0 at 90^0 flexion position, (c) extension of 10^0 from supine position, and (d) external rotation of 20^0 at 10^0 extension position. Three different CCAs were considered for each activity (5^0 , 10^0 , and 15^0)

The risk of BI was very low for flexion and extension activities as there was always a conical clearance of 10^0 and 5^0 respectively throughout the entire hip joint motion (Fig. 3a and c). On the other hand, the risk of BI was high for both IR at 90^0 flexion and ER at 10^0 extension position (Fig. 3b and d). However, it appeared that ER at 10^0 extension position was quite critical.

It was also observed the identified BI regions were very similar to the general BI regions shown in the work of Ohmori, et al. [11]. This was served as a qualitative validation of the method.

B. Activity specific BI

Fig. 4 shows the BI region for four aforementioned activities for 5^0 and 10^0 CCA. It was identified that the BI area for 5^0 CCA was larger for ER activity at extension compared to IR at flexion. Furthermore, the relative location of BI area on femur due to ER and IR for specific CCA, which was somehow difficult to comprehend from CCA specific representation (Fig. 3b and d), was clearly visible in activity specific illustration. There was no flexion activity in Fig. 4 as only CCA up to 10^0 was shown. On the other hand, BI area due to extension activity at 10^0 CCA was suppressed by ER activity at extension position.

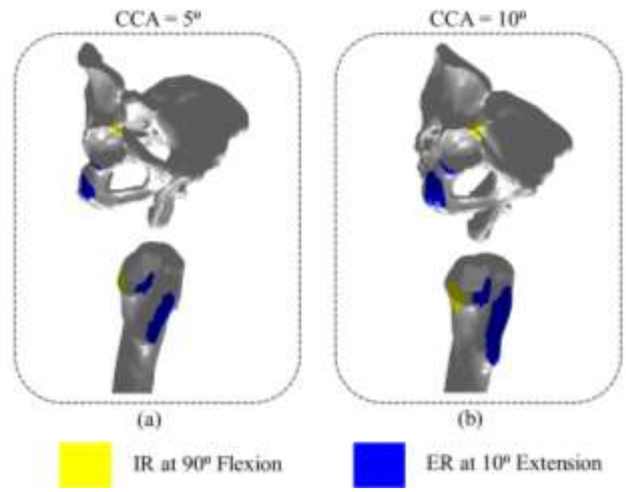

Figure 4: Colour coded representation of BI area due to different activities with CCA (a) 5^0 and (b) 10^0

V. Discussion

BI is a major cause of a restricted range of motion of hip joint and recurrent dislocation after THA. Despite the use of recommended prosthetic designs and positions, and resection of osteophytes and bony prominence, recurrent dislocation occurs, especially in patients with larger bone morphology. Therefore, a method was developed in this paper for identifying subject-specific BI, and subsequently, visualise the BI area on native bone geometries (femur and pelvis). This highlighted BI area would depict the amount of bony area should be resected to improve post THA range of movement of hip joint. During THA, the surgeon would resect the bone areas according to pre-surgical plan to avoid post-operative BI. This will eventually reduce the chance of post-operative dislocation, which could have been occurred due to BI. Besides, this method would be very useful for revision surgery. Using the proposed method, the surgeon could recognise whether the underlying problem for post-operative THA was due to BI or not.

The concept of CCA was introduced to provide a tolerance for the range of motion of an activity, as it is entirely patient-specific. In practice, the surgeons check for BI by moving the femur in different extreme postures, which might vary amongst patients during activities of daily living. Therefore, a CCA was introduced to check for some further clearance along with these extreme positions so that it would even work for a patient who has higher extreme range of motion. For a particular activity, several conical motion could be created by changing CCA, and subsequently, BI could be checked for each CCA. The maximum values of CCA, for which there would be no BI, should be considered as critical CCA (CCA_C). Any CCA values less than CCA_C would not create any BI for the particular posture, and any values greater than CCA_C would definitely create BI. Therefore, smaller value of CCA_C depicts higher chance of BI, and leads to more severe condition.

On the other hand, the effect of different activity for a particular CCA on BI could also be visualised. This would help to understand which activities would be more prone to create BI, and therefore, necessary actions could be taken accordingly. Also, the relative location of the BI area on femur or pelvis due to different activities, which was difficult to understand from CCA specific representation, could be easily recognised though activity specific demonstration.

The resolution of discretizing activity into static postures (N_{Act}) and conical motion into different static positions (N_{Cone}) were important factor. Higher resolution i.e. larger values of both N_{Act} and N_{Cone} would provide accurate results although the computational time would be very high if there was any impingement. In addition, there would be some redundant postures or positions if the resolution became very fine. These redundant postures or positions would not change the final BI area. On the other hand, reducing the value of N_{Act} and N_{Cone} could underestimate the BI area. Therefore, a trade-off value should be chosen for both N_{Act} and N_{Cone} so that accurate BI area could be identified with reasonable computational time.

One of the main limitations of the work was the limited knowledge of the CCA. This could either be found from a clinical study of certain populations or recommendations from experienced surgeons. Besides, the upper limit of CCA could be found by checking PI [12] which was ignored in this study. Accuracy of the STL geometries from CT scan is critical as this would eventually lead to over or under prediction of BI area. In future, effect of geometrical accuracy on predicted BI should also be explored.

VI. Conclusion

This paper introduces a novel method to identify and visualise subject-specific BI area on native bone geometries (femur and pelvis) for different activities of daily livings. The method checks for a conical clearance for a set of postures during an activity, and subsequently, identity and visualise the BI area. This method could potentially be used to examine the effect of different pre-operative plans and hip motion on BI. In addition, this method would guide the surgeons to decide how much and where the bony resection should be performed during THA surgery.

Acknowledgment

The study was funded by Corin Ltd. Three of the authors were employed by Corin Ltd who manufacture and distribute the technology relating to this paper.

References

[1] A. Palit, M. A. Williams, G. A. Turley, T. Renkawitz, and M. Weber, "Femur First navigation can reduce impingement severity compared to traditional free hand total hip arthroplasty," *Scientific Reports,* vol. 7, no. 1, p. 7238, 2017/08/03 2017.

[2] T. Shoji, T. Yamasaki, S. Izumi, S. Hachisuka, and M. J. I. O. Ochi, "The influence of stem offset and neck shaft angles on the range of motion in total hip arthroplasty," journal article vol. 40, no. 2, pp. 245-253, February 01 2016.

[3] T. Shoji, Y. Yasunaga, T. Yamasaki, R. Mori, M. Hamanishi, and M. J. I. O. Ochi, "Bony impingement depends on the bone morphology of the hip after total hip arthroplasty," journal article vol. 37, no. 10, pp. 1897-1903, October 01 2013.

[4] C. F. Scifert *et al.*, "Experimental and computational simulation of total hip arthroplasty dislocation," (in eng), *Orthop Clin North Am,* vol. 32, no. 4, pp. 553-67, vii, Oct 2001.

[5] T. Shoji *et al.*, "Factors affecting the potential for posterior bony impingement after total hip arthroplasty," (in eng), *Bone Joint J,* vol. 99-b, no. 9, pp. 1140-1146, Sep 2017.

[6] A. Malik, A. Maheshwari, and L. D. Dorr, "Impingement with total hip replacement," *J Bone Joint Surg Am,* vol. 89, 2007.

[7] T. Möller and B. Trumbore, "Fast, Minimum Storage Ray-Triangle Intersection " *Journal of Graphics Tools,* vol. 2, no. 1, pp. 21-28, 1997/01/01 1997.

[8] T. Seers, "Fast mesh-mesh intersection using ray-tri intersection with octree spatial partitioning," ed: MathWorks File Exchange, 2015.

[9] P. Franciosa and S. Gerbino, "A cad-based methodology for planar and cylindrical features recognition.," presented at the 4th CIRP International Conference on Intelligent computation in manufacturing engineering, 2008.

[10] A. Palit, "Computational modelling of diastole for human ventricle," PhD, WMG, Warwick University, UK, 2015.

[11] T. Ohmori *et al.*, "Effect of changing femoral head diameter on bony and prosthetic jumping angles," (in eng), *Eur J Orthop Surg Traumatol,* Oct 30 2018.

[12] A. Palit, R. King, Y. Gu, J. Pierrepont, D. Simpson, and M. A. J. A. o. B. E. Williams, "Subject-Specific Surgical Planning for Hip Replacement: A Novel 2D Graphical Representation of 3D Hip Motion and Prosthetic Impingement Information," journal article April 10 2019.