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The Impingement-Dislocation Risk of Total Hip Replacement: Effects of Cup Orientation and Patient Maneuvers

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Abstract— **Hip dislocation is one of the most frequent complications after total hip arthroplasty. Impingement and dislocation might be caused due to misalignment of the acetabular cup during surgery, or performing dislocation-prone activities afterwards. A finite element model was developed to predict the impingement and dislocation behavior of the prosthetic joint, for different combinations of cup orientation and patient maneuver. Four dislocation-prone activities of daily life and 25 cup orientations were analyzed to determine how close they are to the impingement and subsequent dcislocation events. The angular margin results obtained indicated that the sit-to-stand and standing while bending at the waist are prone to dislocation, in particular when the cup anteversion angle is small.**

I. Introduction

The number of total hip arthroplasty (THA) surgeries is increasing each year. At the same time there is a growing incidence of their complications and failures. Dislocation of the prostheses is one of the most frequent and common complications after THA. The prevalence of dislocation has been reported to be between 0.3% and 10% following primary total hip replacement and up to 28% after revision arthroplasty [1].

There are several factors that contribute to the stability of the hip joint prostheses against dislocation, e.g., joint capsule and ligaments, muscles activity, and the design and configuration of the femoral head and acetabular cup. Excessive incision of the ligamentous and capsular tissues, and muscular deficiency would obviously lead to a lower restraining effect and can cause joint instability [2]. Apart from the soft tissue restraints, the design characteristics and the relative configuration of THA components are the main factors affecting the stability behavior of the joint. They control the joint range of motion (ROM) and consequently determine if impingement occurs between the femoral neck and the acetabular cup, as a result of the excessive joint motion. In this situation, the centre of rotation of the femoral head on the cup would move to the rim of the cup. Thus, further motion would lead to the subluxation of the femoral head and its lever-out into dislocation [3]. Although impingement doesn't always lead to dislocation, it is considered as an indicative of following potential dislocation. Furthermore, a recurrent impingement may cause material failure of the acetabular liner, due to the high localized contact stresses at the impingement site [4].

Impingement of the femoral head on the cup, as the main cause of THA dislocation, occurs when the joint's ROM does not correlate with the patient's physical maneuvers. Several investigators have studies the effect of the design of THA components on the joint's safe ROM. Matsushita et al. [5] reported that increasing the femoral offset and head size would improve the ROM after THA significantly. Also, Chandler et al. [6] found that larger heads delay the neck-socket contact, leading to an increased ROM. They further noted that increasing the head size causes a transition from impingement between the prosthetic neck and acetabular liner to the osseous impingement. In general, a large femoral head size is thought to act as a preventative measure for impingement and the following dislocation event [3]. However, in a case of dislocation, it can lead to a more harmful damage due to the larger jump distances [5]. Moreover, a higher head-neck ratio has been reported to enlarge the impingement-free range of joint motion [7-8].

The effect of the orientation of the acetabular cup of the THA on the impingement of the prosthetic component has been also studied by some investigators. The appropriate ranges of the tilt (abduction) and anteversion angles of the cup have been reported to be 30°-50° and 5°-25°, respectively [9]. It has been reported that there is a correlation between the orientation of acetabular component and the dislocation rate of the prosthesis [10-11]. Nadzadi et al. [12] examined different acetabular component orientations and reported the associated ranges of motion that involved impingement. Nishii et al. [13] reported that intentionally positioning the cup at low anteversion, to compensate for high femoral neck anteversion, might predisposes the hip to postoperative dislocation.

In a previous study, Pedersen et al. [3] examined the neck-on-cup impingement occurrence during a number of dislocation-prone activities at different cup positions. Their results indicated that of the 175 combinations of cup position and kinetic challenge, 96 situations were impingement involved. The purpose of the present study was to investigate

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the interrelationship between the orientation of the acetabular component of the THA and the patient's maneuvers with the risk of impingement and the following potential dislocation. A finite element model of THA is developed to analyze the combinations of acetabular cup orientations with the hip joint kinematical and force data associated with instances of dislocation-prone maneuvers. The angular proximity of the joint configurations to the impingement event is found to determine which combinations and instances are risky. Also, the stresses induced to the acetabular cup are analyzed to investigate their possible failure. The results are employed to reveal the safest cup orientations and the risks involved in the daily activities of THA patients.

II. Materials and Methods

In this study, we simulated the mechanisms of THA impingement using a 3D finite element model of the prosthetic femur and acetabulum (Fig 1) in ABAQUS (Explicit version 6.10-1). The femoral head and neck were assumed to be made of stainless steel and were represented by a sphere and an incomplete cone, respectively. The head radius and the head-neck ratio of the femoral component were considered to be 24 mm and 2.89, respectively. Two other head-neck ratios of 2.39 and 1.55 were also modeled and analyzed to investigate the effect of this parameter on the dislocation behavior of the THA. The acetabular component was modeled as an articulating hemisphere with its center coinciding with that of the femoral head. It was positioned in 25 orientations with combination of 30, 40, 50, 60, and 70 degrees abduction and 0, 10, 20, 30, and 40 degrees of anterevsion

The acetabular cup was assumed to include an Ultra High Molecular Weight Polyethylene (UHMWPE) liner with 8 mm wall thickness. In order to simulate the visco-elastic-plastic behavior of the UHMWPE, an elastic-plastic material model with isotropic hardening properties was implemented. We adapted the equation developed by Fregley et al. [14] with n = 3 and the Young's modulus, Poisson's ratio and yield strength of 945 MPa, 0.45 and 23.56 MPa [15]. To satisfy the input requirements of ABAQUS, the nonlinear equation of UHMWPE mechanical behavior was converted into eight segments. Considering the high stiffness of the femoral component in comparison with acetabular cup, it was modeled as a rigid analytical surface to facilitate the computations [16].

The boundary conditions of the FE-model consisted of an input sequence of prescribed incremental rotations of the femoral head, along with corresponding modulation of the hip joint contact forces. Three angles were used to indicate the orientation of the femoral head with respect to the acetabular cup, including flexion, tilt (abduction) and anteversion [1]. The force vector of the hip joint was applied to the centre of the femoral head and was considered to have three components in the posterior-anterior, inferior-superior and medial-lateral directions.

The geometrical and force boundary conditions were determined based on the kinematic and kinetic data of daily maneuvers reported by Nadzaki et al. [16] in which the extension/flexion, abduction/adduction, and exorotation /endorotation angles, as well as the joint force vectors, were collected form 10 subjects and analyzed using inverse dynamics. Four posterior dislocation-prone and an anterior dislocation-prone maneuvers were analyzed to evaluate their risk of dislocation and determine their angular safety margins quantitatively. These maneuvers included sit-to-stand from a low height chair (SSL), erectly seated leg crossing (XLG), seated while reaching to the floor such as shoe tying (TIE), and standing while bending at the waist to pick up an object on the floor (STOOP).

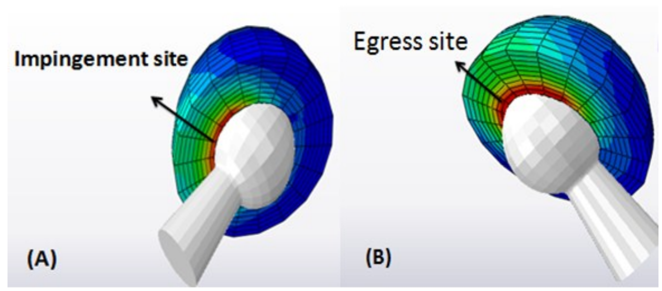

Fig. 1. The finite element model of the THA and the resulting Von Mises stress contours on the cup liner: (A) at the impingement site, and (B) at the egress site.

The finite element model was executed using ABAQUS/Explicit version 6.10-1. Hexahedral 8-nodes elements with linear interpolation were used to discritize the model components. The minimum number of elements was found using a convergence test. The model was highly nonlinear, both geometrically and physically, due to the large deformations and nonlinear material definition. However, with employment of a rigid analytical surface for modeling the femoral head, we could analyze a wide variety of joint geometrical and force configurations for each instance of each maneuver within a short time step.

In order to reveal the impingement risk involved in the different combinations of cup orientation and patient maneuver, the angular margin for the impingement occurrence was defined as a risk measure. For a given joint configuration, e.g., cup orientation and maneuver instant, this measure specifies the smallest angle that the femoral neck should rotate in order to contact the edge of the cup. It is obvious that a larger margin is indicative of a lower risk of impingement and the following potential dislocation. A zero degree angle, on the other hand, represents a configuration in which approximately no gap exists between the femoral neck and the cup edge and impingement would occur.

III. Results

The results of the finite element analysis, indicating the Von Mises stresses induced due to the impingent of the femoral head on the acetabular cup, are shown in figure 1. A localized high contact stress was observed on the cup liner in both the impingement and egress sites. The effect of head-neck ratio on the range of motion, and the dislocation resisting moment of the prosthetic hip joint about the cup centre are illustrated in figure 2. While the range of motion was smaller for smaller head-neck ratios, the maximum of resultant resisting moments were nearly identical for different ratios.

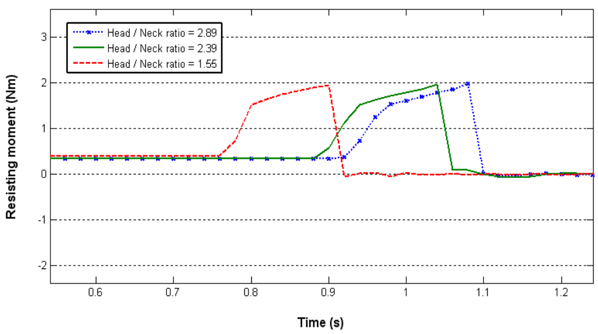

Fig 2. The effects of head-neck ratio on the range of motion and the dislocation resisting moment of the prosthetic hip joint about the cup centre.

Figure 3 illustrates the angular margins to impingement for different combinations of cup orientation and patient maneuver. The tilt and anteversion angles that describe the cup orientation during implantation are represented by α and β, respectively. The intersection point of the angular margin curve with the time axis represents an impingement event. After an impingement instance, the curve might truncate or continue for the rest of the maneuver. The first condition represents a dislocation event, while the latter indicates that the moment resulted from impingement is not sufficient to cause a dislocation.

For the SSL maneuver (Fig 3.a), the angular margin to impingement and dislocation was large at the start and the end of the maneuver. However, it was very small in the middle instants. All cup orientations were predicted to experience impingement throughout the maneuver, except for those with very high anteversion and tilt angles. Even for such cup orientations, however, the safety margin was quite small, e.g., 8° for a 70° tilt and 40° anteversion configuration. For XLG (Fig 3.b), a nearly fixed angular margin was found throughout the maneuver. The margin was most sensitive to the cup anteversion angle with negligible effect from the tilt angle. In general, a sufficiently high angular margin was found for anteversion angles larger than 20°.

The angular margin of the TIE maneuver to impingement decreased gradually from the start of the movement to its end. It was again most affected by the cup anteversion angle and found to be sufficiently far from impingement at anteversion angles larger than 30°. For the STOOP maneuver, the angular margin to impingement was quite large at the start, however, it decreased dramatically towards the end of manuver. Most cup orientations experienced impingement and even for the one with a larger than zero margin (tilt=70° and anteversion=40°) the risk was quite high due to the small distance from impingement.

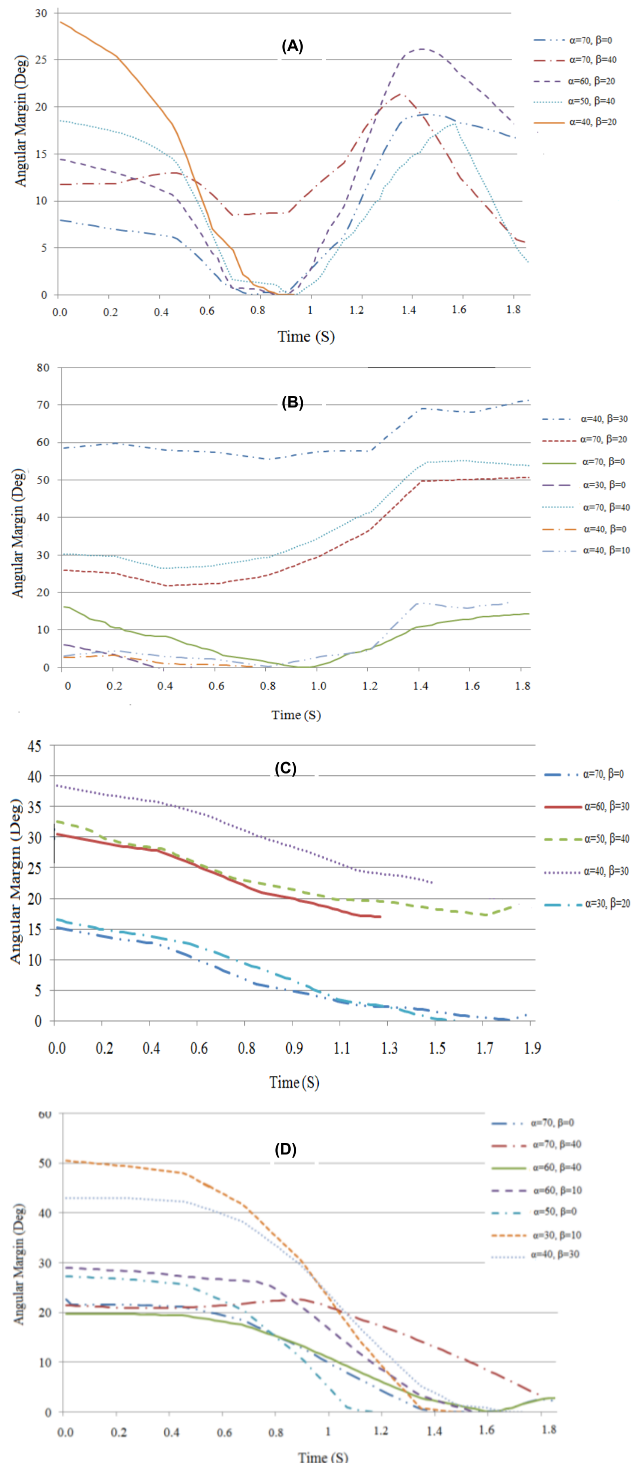

Fig. 3. The angular margins to impingement occurrence for difference cup orientations and patient maneuvers examined: (A) sit-to-stand from a low height chair (SSL), (B) erectly seated leg crossing (XLG), (C) seated while reaching to the floor such as shoe tying (TIE), and (D) standing while bending at the waist to pick up an object on the floor (STOOP). The tilt and anteversion angles that describe the cup implantation orientation are represented by α and β, respectively.

IV. DISCUSSION

The results of our finite element model for the effect of head-neck ratio on the ROM and the resisting moment of the prosthetic hip joint about the cup centre are consistent with the experimental data reported by Kluss [3]. The head-neck ratio affected the impingement free range of motion, but had no effect on the resisting moments against femoral head dislocation. We used the results of the model further to investigate the risk of THA impingement involved in different combinations of cup orientation and patient maneuver. Such information has not been reported before and is of much clinical importance. It not only allows one to predict that whether dislocation occurs at a special joint geometrical and force configuration, similar to former studies, but also it reveals how close this configuration is to the nearest dislocation event. In other words, the anticipation of dislocation is not limited to yes or no, but the safety margin against impingement and the following potential dislocation is also indicated.

The results of our study suggest that the XLG and TIE maneuvers are safer than the SSL and STOOP maneuvers with larger angular margins to impingement. For the SSL maneuver, the angular margin curve often continued after intersecting with the time axis, at a small period in the middle of the movement. This suggests that the impingent event experienced during this maneuver would not necessarily be followed by a dislocation event. However, the localized stresses at the impingement site might damage the cup liner [3]. For the STOOP maneuver, the angular margin to impingement was very small at the ending instances of the movement for all cup orientations examined. This suggests that the risk of impingement and following dislocation is high for this maneuver.

Our results also indicated that the angular margin curves were most sensitive to the cup anteversion angle with a lower contribution from its tilt orientation. A high anteversion angle always improved the joint's behavior against impingement, by providing a larger angular margin. These results are in good agreement with those reported by previous investigations [12].

The quantitative analysis of our study gives more insight into the factors that influence the impingement and dislocation behavior of the THA. However, our results should be treated with caution. The kinematics and kinetics patterns of the dislocation-prone maneuvers might be different among different patients. Thus, the predicted impingement and dislocation may not occur in practice. In such condition, however, the cup failure is still prevalent at the head-liner interface that would require revision surgery or closed reduction [17]. Furthermore, mal-positioning of the cup in combination with some manoeuvres may entail the prosthetic head to slip out of the cup without impingement [16]. Nevertheless, our study ignores the stabilizing contribution of the passive and muscular soft tissue. In cases of sufficient pseudo-capsular tissue and strong muscles, the predicted dislocation behavior might be different [2].

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REFERENCES

[1] J. Parvizi, "Revision total hip arthroplasty for instability: surgical techniques and principles", *J Bone Joint Surg Am,* 2008; 90, pp. 34–42.

[2] J. Elkins, J. Nicholas, J. Stroud, M. James Rudert, "The capsule's contribution to total hip construct stability – A finite element analysis", *J Orthop Res,* 2011; 29 (11), pp. 1642-8

[3] D. Kluss "Influence of femoral head size on impingement, dislocation and stress distribution in total hip replacement", *Med Eng Physics*, 2007; 29, pp. 465-471.

[4] D. R. Pedersen, J. J. Callaghan, T. D. Brown, ''Activity-dependence of the safe zone for impingement versus dislocation avoidance", *Med Eng Physics*, 2005; 27, pp. 323-328.

[5] A. Matsushita, Y. Nakashima, S. Jingushi, T. Yamamoto, A. Kuraoka, Y. Iwamoto, " Effects of the femoral offset and the head size on the safe range of motion in total hip arthroplasty," *J Arthroplasty*, 2009; 24, pp. 646-651.

[6] D. R. Chandler, R. Glousman, D. Hull, P. J. McGuire, I. S. Kim, I. C. Clarke, "Prosthetic hip range of motion and impingement: The effects of head and neck geometry", *Clin Orthop,* 1982; 166, pp. 284–91.

[7] B. R. Burroughs, B. Hallstrom, G. J. Golladay, D. Hoeffel, W. H. Harris. "Range of motion and stability in total hip arthroplasty with 28, 32, 38, and 44 mm femoral head sizes - an in vitro study", *J Arthroplasty,* 2005; 20(1), pp. 11-9.

[8] L. D. Noble, R. W. Colbrunn, D. G. Lee, A. J. Bogert, B. L. Davis, "Design and validation of a general purpose robotic testing system for musculoskeletal applications", *J Biomech Eng,* 2010; 132(2):025001.

[9] D. E. McCollum, W. J. Gray. "Dislocation after total hip arthroplasty-Causes and prevention", *Clin Orthop*, 1990; 261, pp. 159–70.

[10] R. S. Turner, "Postoperative total hip prosthetic femoral head dislocations", *Clin Orthop*, 2002; pp. 180-189

[11] K. Widmer, B. Zurfluh, "Compliant positioning of total hip components for optimal range of motion", *J Orthop Res*, 2004; 22, pp. 815-821.

[12] M. E. Nazdaki, D. R. Pedersen, J. J. Callaghan, T. D. Brown "Effects of acetabular component orientation on dislocation propensity for small-head-size total hip arthroplasty", *Clin Biomech,* 2002; 17, pp. 32-40.

[13] T. Nishii, N. Sugano, H.Miki, T. Koyama, M. Takao, H. Yoshikawa, "Influence of component positions on dislocation: computed tomographic evaluations in a consecutive series of total hip arthroplasty", *J Arthroplasty,* 2004; 19(2), pp. 162-164.

[14] B. J. Fregley, Y. Bei, M. E. Sylvester, "Sylvester ME. Experimental evaluation of an elastic foundation model to predict contact pressures in knee replacements", *J Biomech,* 2003; 36, pp. 1659–68.

[15] F. C. Eichmiller, ''Mechanical properties of ultra high molecular weight polyethylene NIST reference material RM 8456'', In: *Transactions of the 27th Annu. Meeting of Society for Biomaterials*, 2001; pp. 472.

[16] M. E. Nazdaki, D. R. Pedersen, H. J. Yack, J. J. Callaghan, T. D. Brown, "Kinematics, kinetics, and finite element analysis of commonplace maneuvers at risk for total hip dislocation", *J Biomech,* 2003; 36, pp. 577-591.

[17] E. J. McPherson, W. M. Costigan, M. B. Gerhardt, L. R. Norris, "Closed reduction of dislocated total hip with S-ROM constrained acetabular component", *J Arthroplasty*, 1999; 14(7), pp. 882-5.