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Brief communication (Original)

Stress analysis of a polyethylene acetabular component in the extreme flexion position—a finite element analysis

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Background: Many factors cause impingement of the femoral neck and polyethylene liners. Impingements definitely increase the rate of polyethylene wear. This effect has been a major cause of revision hip surgery. Squatting and sitting cross-legged are specific sitting positions typically used by Asian people, including Thai. These types of positions may cause impingements and abnormal stress distributions, resulting in massive destruction of polyethylene liners.

Objective: To analyze the effects of squatting and sitting in a cross-legged position in total hip replacement patients using finite element analysis.

Methods: A three-dimensional finite element model was developed to study the effects of squatting and sitting in a cross-legged position. The study was divided into two parts. First, mean hip ranges of motion of sitting positions were analyzed. Second, hip ranges of motion at one standard deviation were also analyzed. Locations of the impingement area and stress distribution were demonstrated using finite element software.

Results: Squatting and sitting cross-legged at one standard deviation obviously cause significant impingement at the superior part of the polyethylene liner. Maximum principal stresses are 103 MPa and 24.5 MPa in squatting and sitting cross-legged, respectively. There is no impingement when the mean hip ranges of motion are used. The distance between the neck and cup are 4.05 mm and 4.15 mm in squatting and sitting cross-legged, respectively.

Conclusion: Squatting and sitting cross-legged can cause significant impingement in commonly used total hip replacements. Massive destruction of the prostheses can develop by the process of the impingement.

Keywords: Finite element analysis, impingement, polyethylene, stress, total hip replacement

Total hip replacement is the criterion standard of treatment for severe degenerative hip disease. The rate of revision surgery approximates 1%–10% in 10 years [1-3]. Longevity of total hip prosthesis depends on prosthesis design, surgical technique, and patient characteristics. The main etiology of failed total hip prosthesis is aseptic loosening. There are many causes for aseptic loosening. Component on component impingement is the major factor. Impingement of the femoral neck on the acetabulum polyethylene can cause dislocation of the prosthesis; increase polyethylene wear rate and polyethylene fracture [1-4]. The range of motion in patients who underwent total hip prosthesis is lower than that of normal hips. In daily life activities, such as walking, walking upstairs or sitting, the range of motion of the hip is important. Trying to perform some extreme positions of the total hip prosthesis may cause acetabular cup–femoral neck impingement [5, 6]. Excessive force compressing the polyethylene liner can increase the rate of wear and incidence of polyethylene fracture. In Asian populations, squatting and sitting in cross-legged positions are used frequently in daily activity. These positions need more range of motion of total hip prosthesis than walking or sitting on a chair [7]. To our knowledge, there is no study regarding the impingement effect of squatting and sitting cross-legged to polyethylene liner. Our hypothesis is that squatting and sitting cross-legged can cause acetabular cup–femoral neck impingement. We used finite element analysis software to identify the area of impingement and stress distribution on the polyethylene liner.

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Method

A three-dimensional model of a total hip prosthesis was created using Solid Work 2010 software. The initial angle of the acetabular component and femoral component was established. Afterwards, the model was adjusted into the angles of squatting and sitting cross-legged positions. The angles of squatting and sitting cross-legged positions were attributed as shown in **Table 1** [7]. Flexion, abduction and external rotation angles from this study were separated into 2 groups: mean and +1 standard deviation. Therefore, four groups of the total hip models were established.

- Squatting (mean)
- Squatting (+1 standard deviation)
- Sitting cross-legged (mean)
- Squatting (+1 standard deviation)

The four total hip models were examined to identify which position can demonstrate component-on-component impingement. The impingement models were selected. Subsequently, the impingement models were created using LS-PREPOST software (Livermore Software Technology Corporation). Stress distributions on the polyethylene liner were demonstrated using LS-DYNA software, version 971.

The prosthesis model is composed of four components. First, a metal acetabular shell, made from a titanium alloy, which had a Poisson ratio 0.3, elastic modulus 110 GPa, thickness 3.8 mm, and diameter 50 mm. Second, a polyethylene acetabular cup, which had a Poisson ratio 0.45, elastic modulus 0.63497 GPa, yield strength 24.5 MPa, thickness 7.2 mm, chamfer 45°, and no extended rim liner. Third, a metal femoral head, made from titanium alloy, which had a diameter 28 mm and chamfer 45°. Last, a metal femoral neck, made from titanium alloy, which had a trapezoidal shape, neck-shaft offset 34 mm and neck-shaft angle 125°.

We used an acetabular shell size of 50 mm and a femoral head size of 28 mm because of these were the most common sizes used in our hospital. The models were created without a locking mechanism because of its complexity and no obvious effect on the outcome. The extended rim liner was eliminated from the acetabular model because of it would demonstrate more chance of impingement. Acetabular abduction and anteversion angles were 45° and 15°, respectively. Femoral anteversion angle was 15°.

The total hip model was adjusted into four positions as described previously. We found that there was no impingement after the femoral component was rotated into the mean angles of squatting and cross-legged sitting positions. Therefore, it was not necessary to create a finite element model of these two positions. By contrast, we found the impingement of the femoral neck on the acetabular liner when using the +1 standard deviation angles of squatting and cross-legged sitting positions. Accordingly, we selected these two models and subjected them to finite element analysis.

A finite element mesh was created from the models of the +1 standard deviation angles of squatting and sitting cross-legged positions using LS-PREPOST software. The models comprised of three components. First, the acetabular metal shell had 7,680 hexagonal elements and 9,805 nodes. It was titanium material, had a fixed rigid element, no motion, and no deformation. Secondly, the polyethylene acetabular cup was composed of 22,400 deformable continuum hexagonal elements and 25,569 nodes. It had a Poisson ratio of 0.45, elastic modulus of 0.63497, and yield strength of 24.5 MPa. It was connected to an acetabular metal shell by tied type. Finally, the femoral head and neck was comprised of 2,204 quad and tri elements and 2,228 nodes. It was made of chromium material and a rigid element. The femoral head was connected to the polyethylene cup by surface-to-surface contact.

Table 1. Angles of the hip in a squatting position and in a cross-legged sitting position

Angles position	Squatting		Sitting cross-legged	
	Mean	+1 SD	Mean	+1 SD
Flexion (Z-axis)	95°	121°	83°	118°
Abduction (X-axis)	26°	26°	34°	48°
External rotation (Y-axis)	–9°	10°	5°	22°

Stress distribution was calculated using motion and compression of the two materials. Therefore, the joint reaction force was not included in the experiment. In the squatting position, the femoral component was assigned as a 121° flexion angle (Z-axis) and 10° external rotation angle (Y-axis). Subsequently, the abduction angle (X-axis) was started at 16□ then moved around the X-axis until the angle reached 24.5°. The timing of motion was set as 1 s. Afterwards, the finite element analysis software was used to calculate the stress distribution at the area of impingement. In the cross-legged sitting position, the femoral component was assigned as 118° flexion angle (Z-axis) and 22° external rotation angle (Y-axis). Subsequently, the abduction angle (X-axis) was started at 19° then moved around the X-axis until the angle reached 25°. The timing of motion was set as 1 s. Afterwards, the finite element analysis software was used to calculate the stress distribution at the area of impingement. We could not apply the degree of abduction suggested by Hemmerich et al. because the angles were excessive. The finite element analysis software could not calculate the stress distribution because excessive force, more than the ultimate tensile strength, would eventually cause the fracture of the polyethylene.

Results

Squatting when the hip position was 121° flexion, 24.5° abduction, and 10° external rotation demonstrated impingement between the femoral neck and the superior part of polyethylene liner at about the 12-o'clock position as can be seen in **Figure 1A**). Maximal principal stress was 103 MPa. Maximum displacement was 3.1 mm. Contour of effective stress was shown in **Figure 1B**.

Sitting cross-legged when the hip position was 118□ flexion, 25° abduction, and 22° external rotation demonstrated impingement between the femoral neck and the superior part of polyethylene liner about the 12-o'clock position as shown in **Figure 2A**). Maximal principal stress was 24.5 MPa. Maximum displacement was 2.5 mm. The contour of effective stress was shown in **Figure 2B**.

Discussion

Impingement between the femoral neck and polyethylene liner cup is multifactorial. To our knowledge, there is no study regarding the relationship between impingement and sitting in extreme positions, such as squatting and sitting cross-legged. Most of literature is from western populations where squatting and sitting cross-legged are not frequently used in activities of daily living compared with Asian populations.

This study demonstrates the high possibility of impingement from sitting in an extreme position of the hip. The result of these positions can cause excessive stress on polyethylene liners.

We can directly apply the result of the study to the patients by giving advice to avoid squatting and sitting in a cross-legged position after total hip replacement. However, the design of total hip replacement in the future should take this problem into consideration.

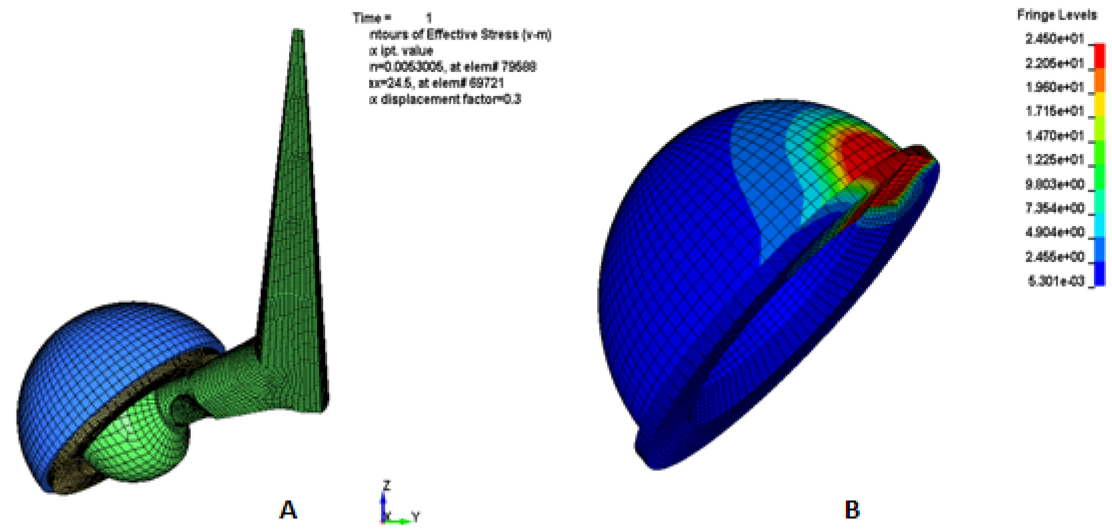

Figure 1. Position of the total hip prosthesis (**A**) and contour of effective stress (**B**) in a squatting position

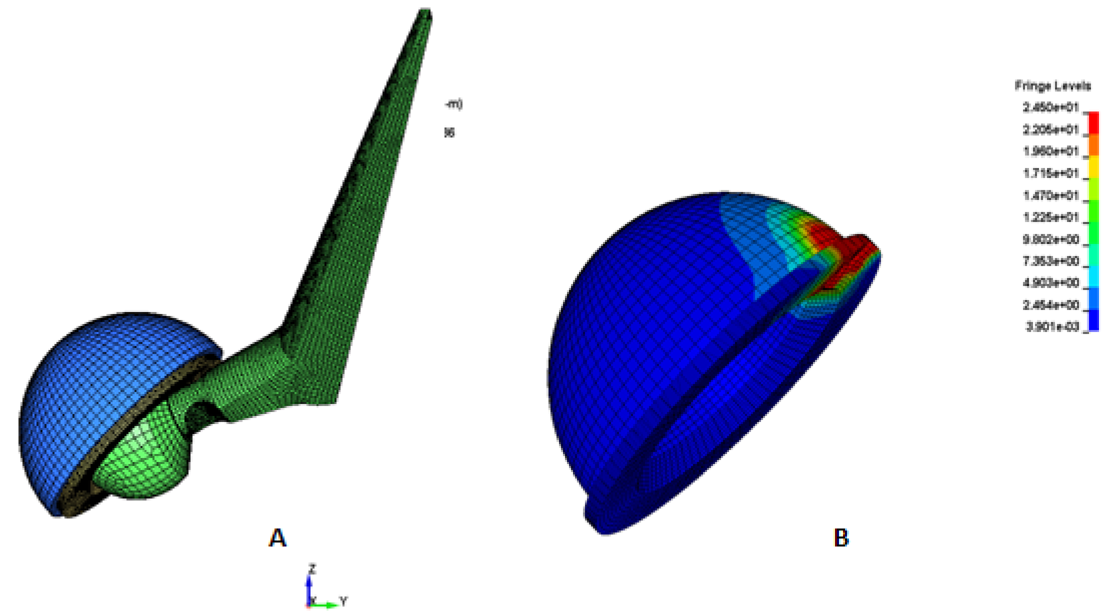

Figure 2. Position of the total hip prosthesis (**A**) and contour of effective stress (**B**) in a cross-legged sitting position

Conclusion

Squatting and sitting cross-legged can cause impingement between the femoral neck and the superior part of polyethylene liner at about the 12-o'clock position. The excessive stress was able to cause damage of polyethylene in total hip prosthesis when a 28 mm femoral head size and 34 mm femoral offset were used. Patients who have total hip prosthesis should avoid squatting and sitting cross-legged.

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