Effect of High Hip Center on Stress for Dysplastic Hip

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Abstract

High hip center reconstruction has been advocated in treating deficient acetabulum. However, there is no consensus on the clinical outcome of this technique. In addition, it remains unclear to what extent this technique restores the normal hip biomechanics. The goal of this study was to investigate stress above the acetabular dome in response to a range of high hip center positioning for Crowe type I and II hip dysplasia. This study consisted of 2 main parts, radiologic and biomechanical. Pelvic radiographs of 18 patients were studied to determine the amount of displacement of the hip center in the superior direction compared with the normal side. Second, qualitative and quantitative changes in stress on cortical and trabecular bone in the region of the acetabular dome as a result of superior displacement of the hip center were analyzed with subject-specific finite element models. The results showed that the range of the hip center position in the superior direction for Crowe type I and II hip dysplasia was 0 to 15 mm above the contralateral femoral head center. When superior displacement of the hip center exceeded 5 mm above the anatomic hip center, cortical bone mass on the 2 thickest cross-sections above the acetabular dome decreased quickly and the stress value on posterolateral cortical bone was obviously lower than the normal level. This study showed that to restore the normal load above the acetabular dome, there is a limit of 5 mm above the anatomic hip center for high hip center acetabular reconstruction for Crowe type I and II hip dysplasia.
Total hip arthroplasty (THA) is one of the most successful reconstructive surgeries and greatly improves patient quality of life. Although anatomic reconstruction of the acetabulum results in the best outcome, anatomic positioning of the cup during THA is often difficult to achieve as a result of hip dysplasia and bone deficiency.\textsuperscript{1,2} The high hip center technique, which has been advocated as a compromise in treating deficient acetabulum, is defined as reconstruction of the hip at a high center located more than 35 mm from the inter-teardrop line or 15 mm higher than the approximate femoral head center.\textsuperscript{3,4} There is no consensus on the clinical outcome of this technique.

Previous studies reported biomechanical data unfavorable to high hip center placement. Doehring et al\textsuperscript{5} used an experimental study to assess the initial stability of implants with increasing positioning of an uncemented acetabular cup and showed that superior and lateral positioning of the hip center 25 mm above the femoral head center led to an increase in implant micromotion. Pagnano et al\textsuperscript{4} reported unfavorable long-term clinical results with high hip center reconstruction in Crowe type II hip dysplasia. Cups that were more than 15 mm superior to the center of the femoral head without lateral displacement had an increased rate of loosening and revision. Similarly, Yoder et al\textsuperscript{6} concluded that the risk of loosening was 4 times greater if the hip center was raised 30 mm above the teardrop. Nevertheless, the high hip center technique in primary or revision arthroplasty for peri-acetabular bone deficiency has been proposed as a valuable alternative by many authors. Hendricks and Harris\textsuperscript{7} reported a low rate of implant aseptic loosening after a long-term follow-up study in which the high hip center technique was adopted for revision total hip arthroplasty in selected patients with severe acetabular bone loss. Christodoulou et al\textsuperscript{8} investigated the rate of polyethylene wear and long-term survivorship in patients with arthritis secondary to congenital hip disease when placing the acetabular cup at a high nonanatomic position and showed that the high hip center technique resulted in long-term survivorship of the implants.

Considering the variable clinical outcomes resulting from the high hip center technique, there is no standard high hip center technique to guide the process of acetabular reconstruction for a certain type of hip dysplasia. In addition, it remains unclear to what extent the high hip center technique restores normal hip biomechanics, particularly the loading profile above the acetabular dome.

Given the questions raised by these reports, the goal of this study was to investigate the range of high hip center positioning and its effect on stress distribution above the acetabular dome for Crowe type I or II hip dysplasia. The authors radiographically obtained the range of hip center position in the superior direction after placing the cup in a hip with dysplasia. The changes in stress distribution on cortical and trabecular bone as a result of superior displacement of the hip center were then described using finite element models. The authors quantified the variation of stress level above the acetabular dome with increasing superior displacement of the hip center.

**Materials and Methods**

This study consisted of 2 main parts, radiologic and biomechanical. The goal of the radiologic study was to find the range of hip center position in the superior direction after acetabular reconstruction in Crowe type I or II hip dysplasia. Only patients with no history of surgery or trauma before THA were included. Those with nonstandard radiographic findings or deformed pelvises were not included. Pelvic radiographs of 18 patients (16 female and 2 male) with unilateral Crowe type I or II hip dysplasia and a contralateral normal hip that had undergone cementless THA on the affected side were evaluated. The mean age at the time of arthroplasty was 57.7 years (range, 33-73 years), and 48-mm and 50-mm Pinnacle acetabular cups (DePuy, Warsaw, Indiana) were used for 7 and 11 cases, respectively. In 5 cases, screws were used to enhance cup fixation. All radiographs were obtained on postoperative day 1. The radiographs were studied to determine the amount of displacement of the hip center in the superior direction compared with the normal side. The authors considered the inter-teardrop line as the reference for superior displacement.\textsuperscript{9} Figure 1 shows the measurement for displacement of the hip center. Superior displacement (millimeters) was measured using the following equation:

\[
\text{Superior displacement} \ (D) = D_1 - D_2
\]

In the second part of the study, the biomechanical consequences of superior displacement of the hip center, such as changes in stress on cortical and trabecular bone in the region of the acetabular dome, were calculated. To generate models for biomechanical analysis, the abduction angle and the size of the acetabular cup were measured and obtained from each patient. A volunteer whose age corresponded to the mean age of the 18 patients was scanned from the proximal
femur to the peak of the iliac crest with a Siemens Emotion 64 computed tomography scanner (Siemens Healthcare, Erlangen, Germany). A normal hemi-pelvis 3-dimensional surface model was generated from the Digital Imaging and Communications in Medicine data using Mimics software (version 10.01, Materialise NV, Leuven, Belgium). The surface model was then used to generate solid finite element models with ANSYS software (version 10.0, ANSYS, Canonsburg, Pennsylvania). A simplified normal hip joint model composed of a hip bone and a femoral hemi-head is shown in Figure 2A. Based on the normal hip joint model, the anatomic hip center was determined by experienced joint replacement surgeons with the assistance of SuperImage software (version 1.2, Cybermed, Shanghai, China). From the radiologic results obtained in part 1 of the study, several reconstructed acetabular models were generated according to the range of superior displacement of the hip center. The reconstructed acetabular models had a reamed cavity in terms of abduction and anteversion angles, respectively. The acetabular component was simplified as a hemispherical cup fitting with a hemi-head (Figure 2B).

A ten-noded tetrahedral element was used for mesh generation of the models. In all models, the meshes included a volumetric mesh of approximately 500,000 elements to assure calculating accuracy.\textsuperscript{10,11} Cortical bone was assumed to be isotropic and homogeneous, with an elastic modulus (17,000 MPa), whereas trabecular bone material was determined with the method of subject-specific material property assignment.\textsuperscript{10,11} In addition, the elastic modulus of the titanium cup and the alumina ceramics were 106,000 MPa and 404,000 MPa, respectively.\textsuperscript{12,13}

Hip joint contact force vector $F$ following the direction of peak hip contact force during a single-legged stance of normal walking was applied through the center of rotation $O$ of the hemi-head model (Figure 2).\textsuperscript{14} Force components in the X, Y, and Z directions (calculated from body weight of 65 kg) were 325 N, -195 N, and 1462.5 N, respectively. Because superior displacement of the hip center alone did not result in an increase in the joint reaction forces,\textsuperscript{2} the same joint force was applied in both the normal hip model and the high hip center reconstructed models. Because head-cup and cup-bone interfaces were not the main focus of this study, contact behaviors were simplified to a linear problem using constraint equations. For geometric constraints, all models were rigidly fixed at the sacroiliac joint and pubic symphysis (Figure 2).

After finite element analysis, stress distribution on the reconstructed acetabular models was compared with that of the normal hip model. Because the distance of 20 mm above the acetabular dome is considered the key region for high hip center acetabular reconstruction,\textsuperscript{15} the authors acquired 5 sections 25 mm above the anatomic hip center, starting with the acetabular dome, with 5-mm increments from inferior to superior (Figure 3). For these sections, the thickness of ilium in the medial to lateral direction was measured and stress distribution on cortical and trabecular bone was analyzed. For

![Figure 2: Hemi-pelvis 3-dimensional model. Normal hip model (A). Example of the acetabular reconstructed model using the high hip center technique (B). Abbreviations: $F$, hip joint contact force vector; $O$, the center of rotation; $X$, $Y$, and $Z$, directions in coordinates.](image)

![Figure 3: Five cross-sections starting from the acetabular dome with 5-mm increments. Red lines represent the region of interest. The black line passes through the anatomic hip center.](image)
quantitative analysis of the stress level above the acetabular dome, 15 nodes within the posterolateral cortical district in these sections were selected uniformly and the average stress of these nodes was calculated, respectively.

**Results**

The range of the hip center displacement in the superior direction was 0 to 15 mm above the contralateral femoral head center. The mean value of the cup abduction angles was 39° (range, 32° to 45°).

Ilium thickness in the medial to lateral direction of the 5 sections above the acetabular dome was 47, 40, 36, 31, and 27 mm, respectively. As shown in Figure 4, in the normal hip model, stress was adequately distributed on both trabecular and cortical bone. However, in reconstructed acetabular models (Figure 5), stress distribution concentrated mainly on the cortical bone. The area of stress distribution on trabecular bone was less than that in the normal hip model. In both the normal and reconstructed models, stress distribution on trabecular bone transferred from anterior to posterior with increasing sections and the highly stressed region of the acetabulum appeared on posterolateral cortical bone.

In the high hip center reconstructed acetabular models using 48-mm and 50-mm cup size, as shown in Figure 5, stress distribution for each section was unaffected by the 2 different cup sizes. When superior displacement of the hip center was confined to 0 to 5 mm above the anatomic hip center, cortical bone mass on sections 1 and 2, which had the thickest ilium above the acetabular dome, was well protected. Furthermore, on sections 4 and 5, which had relatively intact bone mass with the increasing hip center, stress in the region of trabecular bone increased when superior displacement of the hip center was more than 5 mm above the anatomic hip center.

On the reconstructed acetabulum using 48-mm or 50-mm cup size, the tendency for quantitative stress variation on posterolateral cortical bone with the increasing hip center was similar (Figure 6). As with the results of the qualitative analysis of stress distribution, the quantitative analysis of stress level above the acetabular dome also showed that 5 mm above the anatomic hip center was the boundary point. When superior displacement of the hip center was within 5 mm above the anatomic hip center, the stress value on the posterolateral cortical bone was at the same level as that in the normal hip model. However, when the hip center exceeded 5 mm above the anatomic hip center, the stress value decreased remarkably.

**Discussion**

High hip center reconstruction has been advocated as a compromise for use in complex acetabular revision and congenital hip dislocation. Although many clinical studies reported various safety ranges for superior displacement of the hip center, it is difficult to guide the process of acetabular reconstruction for a certain type of hip dysplasia. Most importantly, it is unknown whether high hip center reconstruction restores the normal hip biomechanics and ensures the stability of the acetabular component. To understand the biomechanical implications, this study investigated stress distribution above the acetabular dome in response to a range of high hip center positioning for Crowe type I and II hip dysplasia. The load transfer above the acetabular dome is critical to the stability and survivorship of the acetabular component. Regardless of the position of the hip center, the stress shielding effect remains because of the difference in elastic modulus between the cup and the bone. Previous studies showed that stress shielding from the acetabular cup reduced load level on both trabecular and cortical bone, causing a regional decrease in bone density that can lead to implant migration and loosening. More recent clinical studies further indicated that stress shielding led to more marked bone density loss in trabecular bone than in cortical bone above the acetabular dome. The decrease in trabecular bone density may lead to increased risk of implant loosening and failure.
in trabecular bone density with retention of cortical bone density suggests that stress transfer to cortical bone restores the load level on cortical bone, preserving bone density in the region of the acetabular dome and maintaining the stability of the implant. The authors’ findings regarding stress distribution on cortical and trabecular bone in a range of 20 mm above the acetabular dome are in good agreement with previous clinical studies. The stress distribution helps to explain the

Figure 5: Von Mises stress contours of the 5 sections above the acetabular dome with increasing superior displacement of the hip center for the 48-mm acetabular cup size (A) and the 50-mm acetabular cup size (B) (40° abduction and 15° anteversion; direction and range of the stress value for all sections are the same as in Figure 4).
load transfer from trabecular to cortical bone above the acetabular dome after acetabular reconstruction. Biomechanically, keeping the load on cortical bone above the acetabular dome at the same level as in the normal hip is important to ensure the stability of the acetabular component.

The authors’ findings underline the biomechanical effect of superior displacement of the hip center on cortical bone above the acetabular dome, providing guidelines to preserve biomechanical loading above the acetabular dome. Previous studies determined the thickness of the human ilium above the acetabular dome using a thin transverse section and indicated that there are substantial anatomic limitations to high hip reconstructions 20 mm above the acetabular dome. Although greater ilium thickness means better coverage of the acetabulum cup and greater load capacity, the previous studies did not consider the influence of superior displacement of the acetabular cup on bone mass above the acetabular dome and the load transfer from trabecular to cortical bone after high hip reconstruction. Therefore, ilium thickness alone may not provide an accurate reference for placing the high hip center. According to the study results, cortical bone mass on the 2 thickest sections above the acetabular dome decreased and stress in the region of trabecular bone increased when superior displacement of the hip center exceeded 5 mm above the anatomic hip center. The authors’ findings suggest that if the high hip center exceeds 5 mm above the anatomic hip center, part of the load on cortical bone above the acetabular dome transfers to trabecular bone, disturbing the biomechanical loading above the acetabular dome.

To further describe the effect of superior displacement of the acetabular cup on the load level of cortical bone above the acetabular dome, the authors quantified the stress on posterolateral cortical bone above the acetabular dome. Because the cortical bone mass above the acetabular dome was reduced with superior displacement of the acetabular cup, stress on cortical bone of the sections above the acetabular dome cannot be obtained completely. The authors found that the stress variation on posterolateral cortical bone with the increasing hip center was similar, regardless of whether the 48-mm or 50-mm cup size was used for the reconstructed acetabulum. When superior displacement of the hip center was more than 5 mm above the anatomic hip center, stress on posterolateral cortical bone above the acetabular dome was obviously lower than that in the normal hip model. Therefore, support from cortical bone above the acetabular dome to maintain the stability of the acetabular component would be weakened. With acetabular reconstruction, proper load on cortical bone above the acetabular dome is needed to establish implant stability. To keep the load above the acetabular dome at the same level as that in the normal hip, there is a limit of 5 mm above the anatomic hip center for high hip center acetabular reconstruction for Crowe type I and II hip dysplasia.

**CONCLUSION**

To the best of the authors’ knowledge, this is the first study to assess the load above the acetabular dome with various positions of the hip center. In addition, a range of placement for the high hip center that could ensure a normal load above the acetabular dome was generated specifically for Crowe type I and II hip dysplasia. This study had several limitations. First, simplification of boundary conditions for loading and constraints was adopted in the finite element model. The finite element model with such simplifications has been previously validated by experimental data. Second, long-term follow-up studies on the change in bone density above the acetabular dome for patients with Crowe type I and II hip dysplasia were not included. Future studies incorporating a variety of bone densities could further contribute to the understanding of the biomechanical consequences and help to guide positioning of the high hip center.

**REFERENCES**


