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Finite Element Analysis of the Efficacy of Shelf Acetabuloplasty for Acetabular Dysplasia

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Abstract

Objective: Shelf acetabuloplasty is a type of joint-preserving surgery. There are only a few cases of studying the mechanical evaluations of shelf acetabuloplasty. The objective of this study was to investigate the biomechanical effects of acetabular dysplasia on the acetabular margin and the efficacy of shelf acetabuloplasty using a three-dimensional musculoskeletal model and finite element analysis.

Methods: Subjects were five adult female patients with hip osteoarthritis and acetabular dysplasia who underwent the shelf procedure. Using the data of 4 healthy adult women, joint reaction force in the hip joint during static standing was estimated using Any Body Modeling System.

From the CT images of each subject, finite element models of the pelvis and the right femur were constructed using Mimics and then converted to a three-dimensional finite element model using 3matic. Stress analysis was carried out using Marc Mentat 2011 1.0 finite element analysis software.

In this study, all areas other than soft tissue were considered to be hard bone. In the boundary conditions, the iliac bone and pubic symphysis in the pelvis were fully constrained. Estimated hip joint reaction force was applied as a concentrated load from the distal end of the femur, and von Mises-equivalent stress in the acetabulum was analyzed. The stress distribution, the maximum stress value and the acetabular area applied to the acetabular surface of the acetabulum during resting stance were evaluated before and after the operation.

Results: In the stress distribution of the acetabulum during static standing, the stress was dispersed after the operation, and the maximum stress was decreased. The area of acetabular area was significantly increased after the operation. The maximum stress value was significantly decreased after surgery.

Conclusion: In all cases, the stress distribution of the acetabulum at the time of standstill standing after the operation of shelf acetabuloplasty was significantly dispersed and decreased as compared with the preoperative state.

Keywords: Shelf acetabuloplasty; Finite element analysis; Hip osteoarthritis; Stress distribution

Introduction

The prevalence of osteoarthritis of the hip in Japan is approximately 1.0-4.3% according to plain X-ray diagnosis [1], with osteoarthritis of the hip secondary to developmental dislocation of the hip and acetabular dysplasia accounting for over 80% of cases [2]. Acetabular dysplasia is a condition in which the pelvic acetabulum fails to develop completely and achieves insufficient coverage of the femoral head. In hip joints with acetabular dysplasia, the acetabulum is reportedly subjected to approximately twice the mean stress as that in an unaffected hip [3], with this stress concentrated on the lateral side of the acetabulum [4]. The resulting damage to the articular cartilage and articular labrum causes hip pain and eventually leads to the development of osteoarthritis of the hip [5]. Osteoarthritis of the hip may be treated conservatively with orthotics and pharmacotherapy, or surgically with joint-preserving surgery or hip arthroplasty [6]. Shelf acetabuloplasty is one joint-preserving surgery used to treat osteoarthritis of the hip in patients with acetabular dysplasia [7]. Shelf acetabuloplasty is a type of joint-preserving surgery in which the contact surface area of the acetabulum is augmented by an autologous bone graft to disperse the preoperative concentration of stress. Although the mechanical efficacy of periacetabular osteotomy, another hip-preserving surgery, has previously been demonstrated [8], most studies of shelf acetabuloplasty have focused on either sensory assessments such as pain and discomfort, or X-ray-based two-dimensional morphological evaluation. Few case studies using mechanical evaluations have been reported, and none appear to have addressed questions beyond comparisons and evaluations of the stress generated in cartilage before and after shelf acetabuloplasty [9-11]. The objective of this study was to investigate the biomechanical effects of acetabular dysplasia on the acetabular margin and the efficacy of shelf acetabuloplasty using a three-dimensional musculoskeletal model and finite element analysis.

Materials and Methods

Patients

Subjects were five adult female patients with hip osteoarthritis and acetabular dysplasia who underwent the shelf procedure (Age: 39.8 ± 7.0 years old; height: 155.85 ± 4.19 cm; weight: 53.95 ± 5.07 kg; all with pre-coxarthropathy).

Method

Estimation of joint reaction force: Joint reaction force in the hip joint during static standing was estimated using data from four healthy adult women (Age: 77.5 ± 5.4 years old; height: 148 ± 4.8 cm; weight: 47.25 ± 5.4 kg). Positional data were measured with a VICON MX three-dimensional motion analysis system (Inter Reha Co., Japan), and external force data were obtained using a Force Plate Type 9286B ground reaction force measurement system (Kistler Co., Japan).

Subjects	RF [N]	X component [N]	Y component [N]	Z component [N]
1	409	-72	-2	402
2	211	-20	13	209
3	259	-63	-13	251
4	274	-73	-33	262
Average	288	-57	-8	281

Table1: Estimated hip joint reaction force (RF) during resting standing (X: left trunk direction; Y: back trunk direction; Z: vertically upward direction).

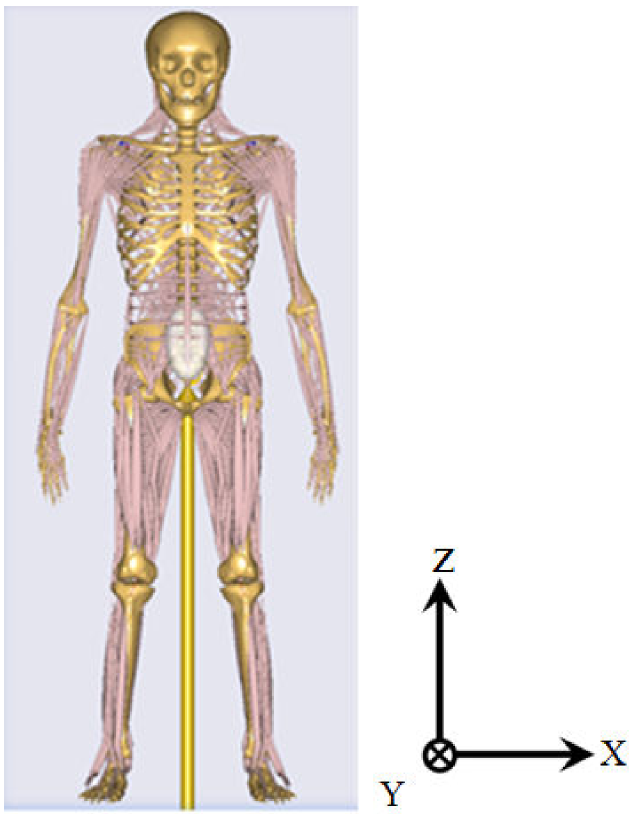

Figure 1: Three-dimensional musculoskeletal model.

The positional and external force data thus obtained were used to estimate hip joint reaction force (Table1) by inverse kinematic and inverse mechanical analyses using Any Body Modeling System (AMS.v. 6.0.5.4379) (Any Body, Technology, Alborg, Denmark) (Figure 1).

Production of finite element models: Finite element models of the pelvis and right femur were created from computed tomography (CT) images of each subject at a slice thickness of 2.5 mm using Mimics (Materialise, Japan) (Figure 2a), which were then converted into three-dimensional finite element models using 3matic (Materialise) (Figure 2b). Stress analysis was carried out using Marc Mentat 2011 1.0 finite element analysis software (MSC Software Co.,Santa Ana,CA,USA).

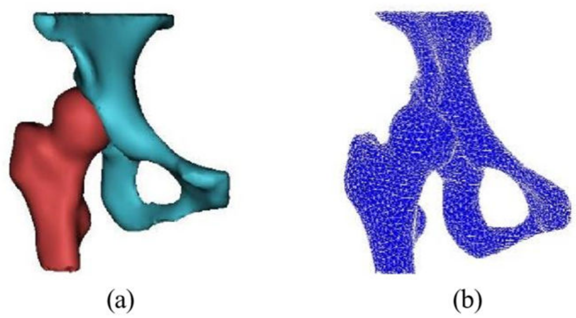

Figure 2: Finite element model. (a) Three-dimensional model. (b) Three-dimensional finite element model.

The three-dimensional finite element model produced in Mimics was imported, and the cartilage and articular labrum between the pelvic and femoral articular surfaces was reconstructed in Marc Mentat. Physical property values of the finite element model were determined with reference to Zhao et al. (Table 2) [8]. Because the objective of this study was to carry out a mechanical evaluation at the

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surface of the cortical bone at the acetabular margin, all areas other than soft tissue were considered to be hard bone.

Material	Young's Module E [Mpa]	Poisson's ratio v
Bone	17000	0.3
Cartilage	15	0.45
Labrum	15	0.45

Table 2: Physical property values for each material.

In the boundary conditions, the iliac bone and pubic symphysis in the pelvis were fully constrained. Estimated hip joint reaction force was applied as a concentrated load from the distal end of the femur, and von Mises-equivalent stress in the acetabulum was analyzed.

Parameters evaluated: The stress distribution, the maximum stress value and acetabular area on the acetabular articular surface during static standing before and after the shelf procedure was calculated. The maximum stress value was calculated as a value obtained by plotting a total of 10 points on the nodal points at the stress concentration point and the surrounding high stress value.

Statistical analysis: The Mann-Whitney U test was used for statistical analysis, with $p<0.05$ regarded as significant.

Results

Figure 3 shows the distribution of stress in the acetabulum during static standing (this figure shows all five patients before and after the shelf procedure). Figure 3a shows preoperative hips and Figure 3b shows postoperative hips. Preoperatively, stress in the acetabulum was concentrated at the acetabular margin, but this stress was dispersed postoperatively and maximum stress was diminished.

The average value of the acetabular area before the operation was 2752 mm^2, and the average value of the acetabular area after the operation was 3476 mm^2, a significant increase in area after surgery (Figure 4).

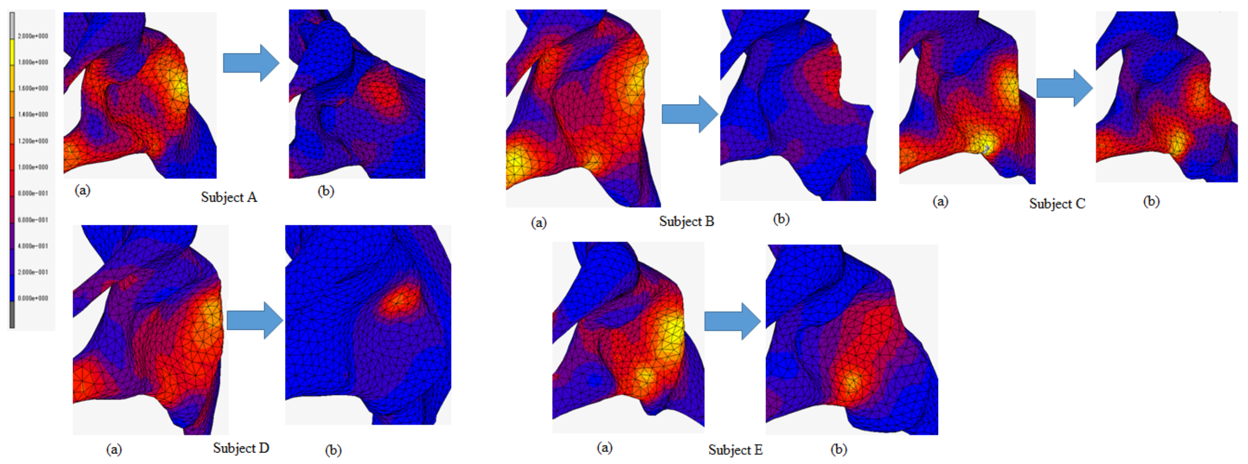

Figure 3: Stress distribution of acetabular portion before and after operation during resting standing position.

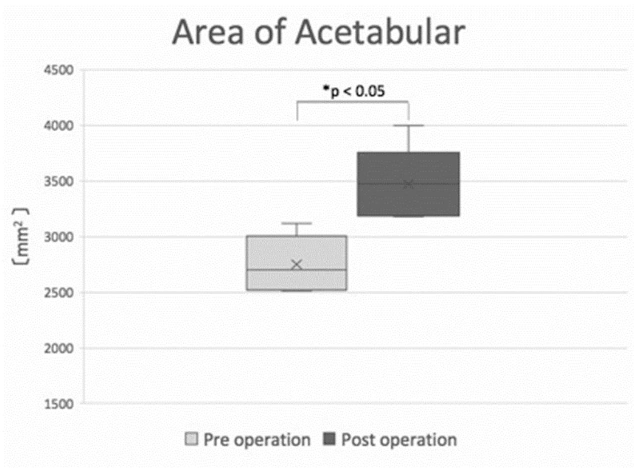

Figure 4: Area of acetabular pre and post operation.

As for the maximum stress value, the average value before the operation was 1.718 MPa, the average value after the operation was 1.114 MPa, and the maximum stress value was significantly decreased after the operation (Figure 5).

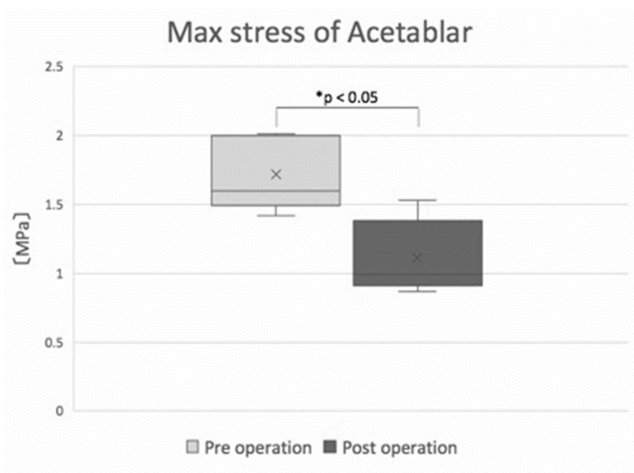

Figure 5: Maximum stress of acetabular pre and post operation.

Discussion

In the shelf procedure, the contact surface area of the acetabulum is augmented with an autologous bone graft to reduce the concentration of the weight-bearing load. This excellent procedure is less invasive than other joint-preserving surgeries and reduces the burden on patients in terms such as the duration of recovery required [7]. Young patients with painful pre- or early coxarthropathy are regarded as the best candidates for this surgery [11-13]. In the modified Spitzy method, a bone graft harvested from between the anterior superior iliac spine and the tubercle of the iliac crest is inserted immediately above the articular surface, and the lateral bone cortex is raised as a bone flap to stabilize the bone graft. However, no clear indicators for the position and angle of the grafted bone remain lacking. In previous studies, postoperative evaluations have been carried out on the basis of therapeutic results, patient sensory assessments, and X-ray-based objective assessments. Finite element analysis is reportedly useful for evaluating stress in the acetabulum [8]. However, no previous study has considered soft tissues in finite element analysis of the shelf procedure. The shape of the acetabulum and the thickness of the acetabular cartilage vary between individuals. Thicker acetabular cartilage is reportedly associated with lower stress, and if this cartilage is thin, stress is concentrated at the acetabular margin [10]. Other studies have also found that if the radius of the acetabular margin is narrowed, the stress in this region increases [14,15]. This suggests that differences in the shape of the acetabulum and the thickness of the acetabular cartilage may affect the location at which stress is concentrated in the articular surface of the hip. This study reproduced not only bone elements, but also the articular cartilage and articular labrum. We found that the shelf procedure dispersed stress in the acetabulum and significantly reduced maximum stress during static standing, representing similar results to those reported previously [10,11]. Maximum stress has been reported to be relatively low and the stress in the acetabular margin is more dispersed in normal hip joints compared with hips showing acetabular dysplasia [14] and augmenting the contact surface area of the joint reduces the stress generated in the articular surface [12]. Artificially increasing the area of coverage at the top of the acetabulum by means of shelf acetabuloplasty may increase the area supporting weight-bearing, both dispersing the stress concentrated at the acetabular margin and reducing maximum stress. As limitations of this research, it is impossible from the CT data that the number of cases is small, and cartilage and joint lips are impossible, so it is estimated that the MRI image data was estimated below, that it is analysis only at resting position.

Conclusion

The biomechanical effects of acetabular dysplasia on the acetabular edge and the effect of shelf acetabuloplasty were examined using a three-dimensional musculoskeletal model and finite element analysis. In all cases, the stress distribution of the acetabulum at the time of standstill standing after the operation of shelf acetabuloplasty was significantly dispersed and decreased as compared with the preoperative state.

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