Dynamic Instability in Young Adults with Symptomatic Hip Dysplasia: Analysis using a Computer-Assisted Image-Matching Procedure

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Research article

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Abstract

Background:

Repeated microtrauma often causes damage to the periarticular soft tissues. This damage, together with the lack of acetabular bony coverage, such as developmental dysplasia of the hip (DDH), can contribute to various degrees of dynamic instability of the hip joint and cause progressive osteoarthritic changes

The purpose of this study was to use an image-matching procedure to compare dynamic instability of the hip joint in patients with DDH who did or did not undergo periacetabular osteotomy (PAO).

Methods:

Six patients (6 hips) with symptomatic DDH were enrolled. A 6-month trial of nonsurgical management was initiated at the first visit. PAO was performed in 3 patients who experienced persistent pain after conservative treatment. The dynamic instability of all 6 hips was evaluated.

Results:

Japanese Orthopaedic Association hip scores improved significantly in all hips regardless of PAO. At the first visit, the center-edge angle, Sharp angle, vertical-center-anterior angle, and acetabular head index were not significantly different between the PAO and non-PAO groups. Dynamic instability was defined as the 3D translation of the femoral head center for the acetabular center at hip abduction angles from 0° to 30°. In the non-PAO group, the mean sagittal, axial, and coronal translations were 2.4 mm, 2.2 mm, and 1.1 mm, respectively, and in the PAO group they were 2.4 mm, 7.2 mm, and 2.7 mm, respectively. There was a significant difference in axial translation between the 2 groups.

Conclusion:

Dynamic instability leads to periarticular soft tissue damage and insufficient bony coverage, and causes progressive osteoarthritic changes. Dynamic instability in the axial plane induces persistent hip pain after nonsurgical management. Affected patients should undergo PAO as soon as possible.

Background

The hip is generally viewed as an inherently constrained joint due to the high degree of bony congruity between the femoral head and acetabulum [1]. Developmental dysplasia of the hip (DDH) is an abnormality of the entire hemipelvis in which there is insufficient anterior or lateral coverage of the femoral head. Conditions with insufficient bony architecture, such as DDH, may constitute a risk factor for dynamic instability. Dynamic instability of the hip joint is characterized by excessive femoral head movement within the acetabulum [2], and is the leading cause of end-stage osteoarthritis (OA) of the hip in patients younger than 50 years. In DDH there is variable progression of degenerative changes over time. This variability can be associated with hip joint stabilizations consisting of the acetabular labrum, ligamentum teres, and capsular structures. Repeated microtrauma often causes damage to the periarticular soft tissues. This damage, together with the lack of acetabular bony coverage, can contribute to various degrees of dynamic instability of the hip joint and cause progressive osteoarthritic changes [3].

Diagnosing dynamic instability of the hip joint can be challenging, and should involve the patient's history, physical examination, available radiographic images, and even dynamic radiographic evaluation [4].

We previously developed a unique computer-assisted image-matching procedure to analyze the kinematics of natural and artificial joints by applying an image window–based analytical method to serial unidirectional X-ray scans. The accuracy of measurements of the patellar bone of a fresh-frozen pig knee joint yielded a root mean square error of 0.02 mm in translation and 0.2° in rotation. [5].

The aims of this study were to evaluate the dynamic instability of the hip joint in patients with symptomatic DDH using the computer-assisted image-matching procedure, and to compare the results between patients who underwent periacetabular osteotomy (PAO) due to persistent pain despite 6 months of nonsurgical management, and those who did not undergo surgery because conservative management resulted in decreased hip joint pain.

Methods

From April 2018 to April 2019, we investigated 6 patients (6 hips) with symptomatic DDH. All patients had bilateral dysplasia of the hip and had pain in one hip joint. The mean age at the time of the first medical examination was 30.2 years (18 to 48). All patients were females. The mean body mass index was 21.6 kg/m^2 (18.9 to 23.0). DDH was classified using the Tönnis et al. system. All hips in this study had Grade 0 DDH, and none had Grade 1, 2, or 3 [6]. None of the patients had undergone surgery during infancy to reduce congenital dislocation of the hip.

At the time of the first medical examination, patients began a 6-month trial of nonsurgical management consisting of patient education, activity modification, physical therapy, and/or anti-inflammatory medications [7].

Surgical management, specifically PAO [8] [9] [10] [11], was performed in 3 patients (3 hips) in whom pain was still present after 6 months of nonsurgical management for DDH (PAO group). The remaining 3 patients (3 hips) reported reduced pain after conservative treatment and did not undergo PAO (non-PAO group). The mean follow-up duration after the first medical examination was 23 months (8 to 41), and the mean follow-up duration after surgery was 11.3 months (8 to 18).

The Japanese Orthopaedic Association (JOA) scoring system was used to evaluate hip joint function [12]. The JOA system consists of a 100-point scale comprising the following subcategories: pain (0 to 40 points), ability to walk (0 to 20 points), range of motion (0 to 20 points), and ability to complete tasks of daily living (0 to 20 points). Higher scores indicate better function. Scores at the final follow-up were compared to those obtained preoperatively.

Radiographic examination was performed both at the first and final medical examinations to calculate the center-edge (CE) angle [13] [14], Sharp angle [15], acetabular-head index (AHI), and vertical-center-anterior (VCA) angle in the false profile view [16].

Image acquisition was performed using a computed tomography (CT) scanner (Philips Brilliance® 64 scanner; Marconi Medical Systems, Best, Netherlands) and an X-ray flat panel detector system (FPD, Zexira®; Toshiba, Tokyo, Japan). CT scans were taken of the hip area from the bilateral anterior superior iliac spines to the distal ends of the femurs. DICOM-compliant CT images were taken under the following conditions: resolution, 512×512 pixels; slice thickness, 0.67 mm; and pixel size, 0.391 mm × 0.391 mm. The CT data were then converted to voxels to construct a 3D gray-scale digital image. The 3D gray-scale model was located in a virtual 3D space, and computer simulation of the radiographic process was carried out to generate virtual radiographic images in which the light source and projection plane parameters were set identical to the actual FPD imaging conditions. The relative geometric relationship between the X-ray light source and the projection plane (flat panel sensors) of the FPD system was determined using a coordinate building frame. The simulated value A of a voxel at a point (x, y) on the project plane was defined by:

$A(x,y) = \sum_{i}^{n} a_i L_i$, where a_i is the value of a property of interest (e.g., bone mineral density) per unit length of the ith voxel through which a virtual X-ray beam passes, L_i is the length of the ith voxel, and n is the number of voxels through which a virtual X-ray beam travels (Fig. 1).

Virtual 2D images generated from the 3D gray-scale model were then compared with the serial X-ray images acquired using the FPD. Correlations of the pixel values between the virtual and real images were used to fine-tune the 3D model (Fig. 2). Multiple small image windows that spanned the bone edge were defined for the image-matching analysis [5].

Using the FPD, DICOM-compliant X-ray images of the hip joint were obtained, each measuring 2048 × 2048 pixels with a 0.148-mm pixel pitch. The hip joint was positioned near the flat panel sensors during motion, and images were taken from the anteroposterior side. The frame rate was set at 3 frames/sec to acquire high-resolution images. The pelvic and femoral coordinate systems were determined based on the study by Cappozzo et al. [17] [18].

Dynamic instability of the hip joint was defined as the mean 3D translation between the maximum and minimum values of the femoral head center for the acetabular center at hip abduction angles from 0° to 30° (Fig. 5).

Clinical assessments and radiographic measurements were completed twice by 2 orthopedic surgeons, each with more than 15 years of experience in assessing hip function. Both surgeons were blinded to the radiographic results at the time of the evaluation. The time between measurements was at least 2 weeks. Intra- and interobserver variances were calculated.

Statistical analysis

The normality of continuous data was assessed with Levene's test. Since the data were normally distributed, the unpaired Student's t-test was used. Intraobserver variances in the JOA hip score were determined by comparing separate radiographic assessments of the same patient, performed by the same observer with at least a 2-week interval between assessments. Intra- and interobserver variances in the JOA hip score were determined by comparing radiographic measurements and are expressed using interclass correlation coefficients (ICCs), with ICC < 0.20 indicating slight agreement; 0.21 to 0.40, fair agreement; 0.41 to 0.60, moderate agreement; 0.61 to 0.80, substantial agreement; and > 0.80 almost perfect agreement [19]. JMP® for Windows version 15.1 (SAS Institute Japan) was used for all statistical analyses. A p value of < 0.05 indicated statistical significance.

Ethics

This study was approved by our institution's Ethics Committee and was conducted in accordance with the World Medical Association Declaration of Helsinki Standard of 1964, as revised in 1983 and 2000. All patients were informed about the study in detail before providing written informed consent for enrollment, including consent for postoperative CT imaging.

Results

The JOA hip scores improved significantly from 67.0 (50 to 86) points at the first medical examination to 97.3 (95 to 99) points at the final follow-up visit in the 3 patients in the non-PAO group, and from 80.7 (74 to 88) points at the first medical examination to 95.7 (87 to 100) points postoperatively in the 3 patients in the PAO group. The JOA hip scores at both the first and final follow-up examinations showed no significant differences between groups. Two intraobserver ICCs were calculated, and both were 0.9 or higher. The interobserver ICCs were also 0.9 or higher. These values indicate almost perfect agreement in JOA hip score measurements.

The CE angle, Sharp angle, AHI, and VCA angle at the first examination in the non-PAO group were 10.3° (4 to 15), 50.7° (47 to 54), 62.8% (55.2 to 67), and 8.7° (1 to 19), respectively, while in the PAO group they were 5.3° (− 8 to 19), 52.7 (49 to 55), 55.3% (42.7 to 69.4), and 12.3° (− 1 to 30), respectively. There was no significant difference between the 2 groups in terms of the radiographic assessments.

None of the 3 patients who underwent PAO developed postoperative infections, paralysis, deep vein thrombosis, or nonunion. Radiographically, the CE angle, Sharp angle, AHI, and VCA angle improved significantly from 5.3° (− 8 to 19), 52.7° (49 to 55), 55.3% (42.7 to 69.4), and 12.3° (− 1 to 30)

to 41), 89.5% (84.9 to 92.5), and 52.0° (43 to 59) postoperatively ($p < 0.05$, $p < 0.05$, $p < 0.05$, and $p < 0.05$, respectively). Two intraobserver ICCs for the radiographic measurements were calculated, and both were 0.9 or higher. The interobserver ICCs were also 0.8 or higher. These values indicate almost perfect agreement.

We used the computer-assisted image-matching procedure to assess the dynamic instability of the hip joint in patients with symptomatic DDH and to compare the non-PAO and PAO groups. In the non-PAO group, the mean 3D translation was 3.4 mm (2.7 to 4.2) and the mean sagittal, axial, and coronal translations were 2.4 mm (2.2 to 2.7), 2.2 mm (1.4 to 3.1 mm), and 1.1 mm (0.4 to 1.8), respectively (Fig. 6a, b, c).

In the PAO group, the mean 3D translation was 6.3 mm (4.2 to 7.7), with no significant difference between the non-PAO and PAO groups. The mean sagittal, axial, and coronal translations were 2.4 mm (0.9 to 2.1), 7.2 mm (5.2 to 8.2), and 2.7 mm (1.1 to 3.7), respectively (Fig. 7a, b, c). The mean axial translation differed significantly between the non-PAO and PAO groups.

Discussion

In DDH, the rate at which degenerative changes progress over time varies among patients, and is associated with hip joint stabilizations consisting of acetabular bony coverage and the acetabular labrum, ligamentum teres, and capsular structures [3]. Both the lack of acetabular bony coverage and damage to the periarticular soft tissues can contribute to hip joint instability to various degrees, and thereby cause progressive osteoarthritic changes.

Surgical treatment of hip joint instability may be divided into 2 general categories: soft tissue procedures and bony realignment. Kraeuler et al. described iliofemoral ligament reconstruction with an Achilles tendon allograft in patients with hip instability due to anterior capsular deficiency [20]. However, in patients presenting with a CE angle < 20 and a VCA < 20, an osteotomy procedure may result in better outcomes. PAO aims to correct the deficient acetabular coverage in hips with DDH and thus prevent secondary OA in patients younger than 50 years. Since PAO is a more invasive treatment, it should be performed only in patients for whom it is appropriate.

It is important to identify dynamic instability of the hip because surgical treatments such as PAO and capsular plication can be effective [21]. In normal hip range of motion, the center of the femoral head moves relative to the center of the acetabulum. Safran et al. demonstrated in a cadaveric model that the femoral head translates a mean of 3.4 mm in the medial–lateral plane, 1.5 mm in the anterior–posterior plane, and 1.5 mm in the proximal–distal plane [22]. In an in vivo study of a native hip using 3D MRI, Akiyama et al. reported that the mean translation from the neutral to the Patrick position in the dysplastic hip was 4.10 ± 1.41 mm. [23].

We investigated the dynamic instability of the hip joint in patients with symptomatic DDH using a computer-assisted image-matching procedure, and compared patients who required PAO due to

al management with patients who experienced reduced pain after conservative treatment and who therefore did not undergo surgery. Dynamic instability of the hip joint was defined as the mean range of 3D translation between the maximum and minimum values of the femoral head center for the acetabular center at hip abduction angle from 0° to 30°. In the non-PAO group, the mean 3D translation was 3.4 mm, while in the PAO group, it was 6.3 mm, with no significant difference between the 2 groups. However, in the PAO group, the axial translation was 7.2 mm (5.2 to 8.2), indicating a significant difference between groups.

It is difficult to detect axial translation on radiographic evaluation. We used kinematic analysis to assess dynamic instability in patients with symptomatic DDH. Patients with at least 5.2 mm of axial translation between the maximum and minimum values of the femoral head center for the acetabular center, at hip abduction angles from 0° to 30°, should be considered as candidates for corrective osteotomy.

Limitations

This study has several limitations. First, femoral head sphericity is associated with age. The acetabulum and femoral head may become incongruent with age, which can cause joint translation during normal hip movement [24]. Second, we did not evaluate dynamic instability of normal hip joints using the computer-assisted image-matching procedure [25]. Finally, our conclusions were not fully definitive due to the small number of cases (n = 6) in this study.

Conclusions

We performed kinematic analysis to evaluate dynamic instability of the hip joint in patients with symptomatic DDH. Dynamic instability in the axial plane of the femoral head center for the acetabular center was associated with persistent hip joint pain after nonsurgical management for 6 months. Patients with axial instability should be evaluated as candidates for corrective osteotomy as soon as possible.

Abbreviations

DDH
developmental dysplasia of the hip
OA
osteoarthritis
PAO
periacetabular osteotomy
JOA
Japanese Orthopaedic Association
CE angle
center-edge angle
AHI

acetabular-head index
VCA angle
vertical-center-anterior angle in the false profile view
CT
computed tomography
ICCs
interclass correlation coefficients

Declarations

Ethical approval

Approval for this study was obtained from the Ehime University Graduate School of Medical Science Ethics Committee, and the study was conducted in accordance with the ethical standards stipulated by the 1964 Declaration of Helsinki and its later amendments.

Consent to Participate

Informed consent was obtained from all participants included in the study.

Consent for Publication

All patients included in this study have given written consent to have their personal data published.

Availability of data and materials

All data and materials generated or analyzed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

Funding

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Authors Contributions

Y Shiraishi, S Sakai, J Miyawaki, N Mashima participated in the conception and design of the study, or analysis and interpretation of data. H Miura participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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Figures

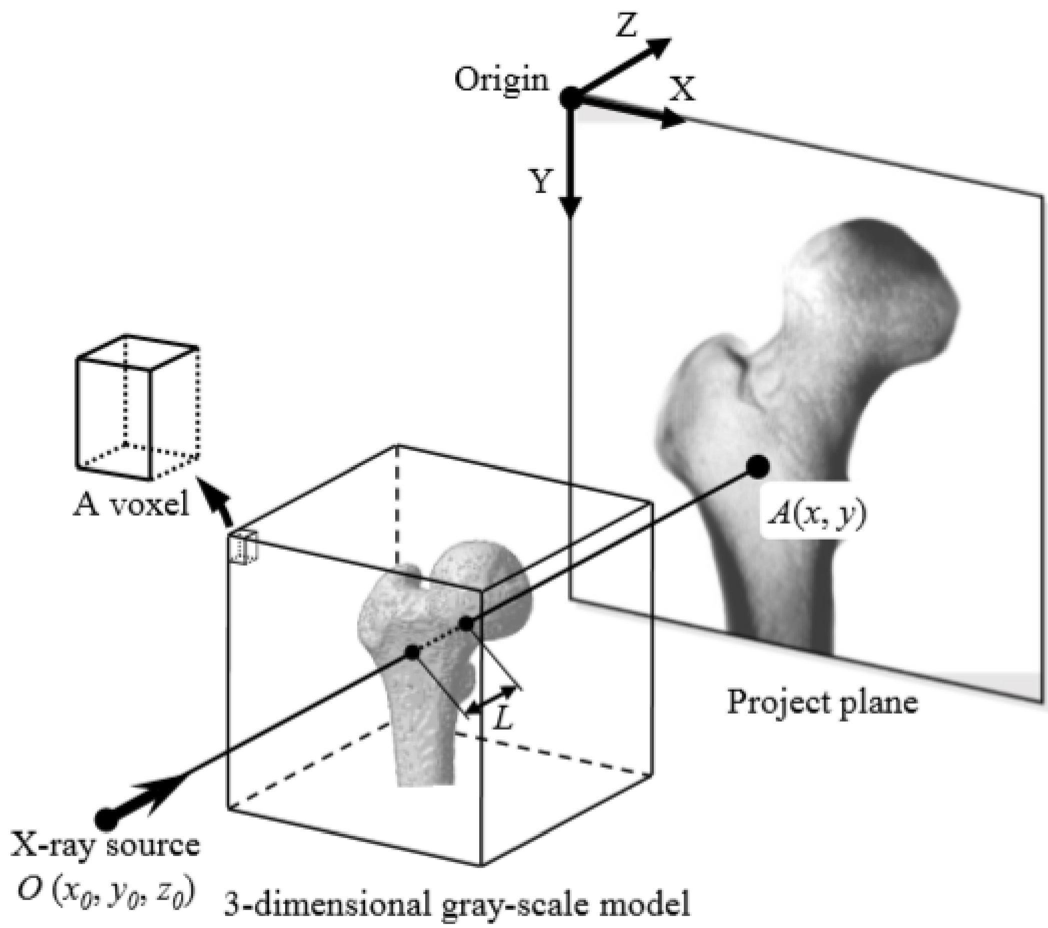

Figure 1

Generation of computer simulation image.

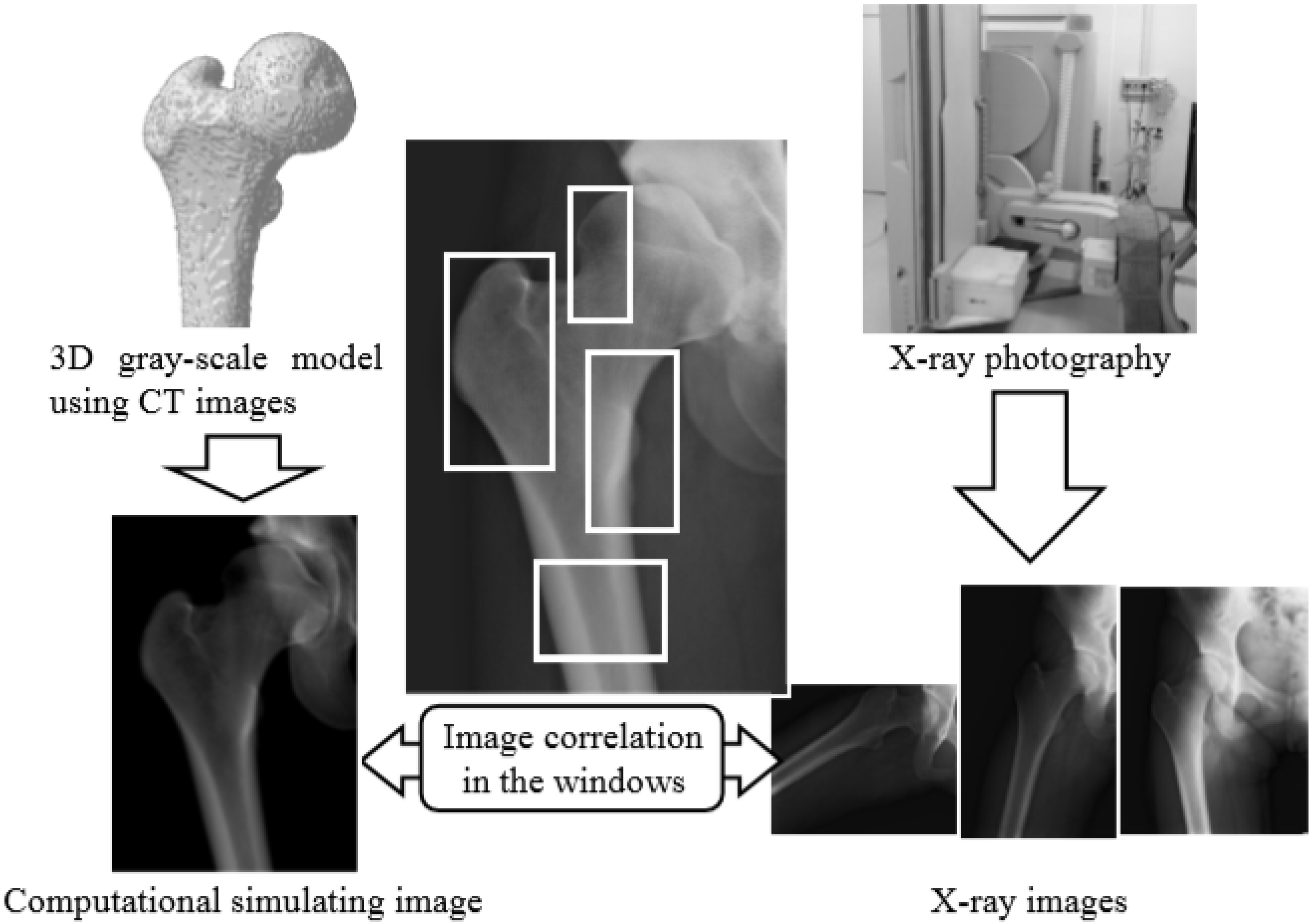

Figure 2

Motion analysis methods using several windows and image correlation.

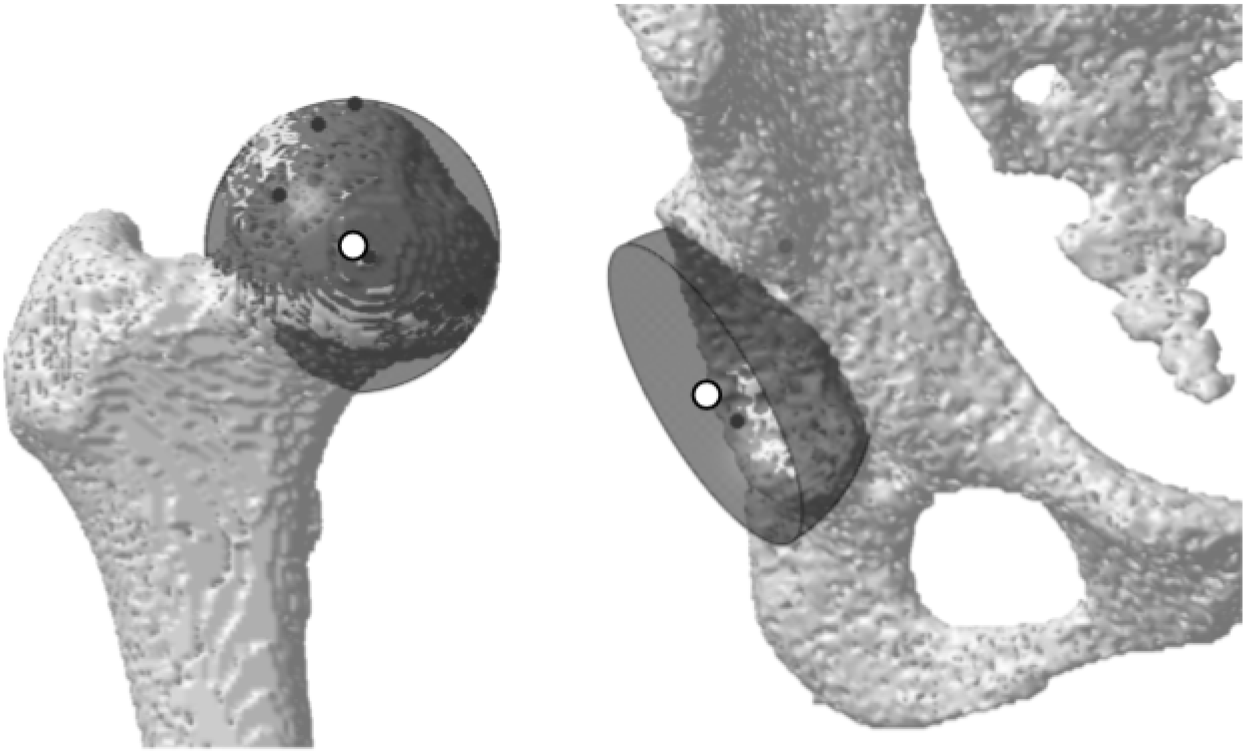

Figure 3

Center of the femoral head and acetabulum using the approximate sphere.

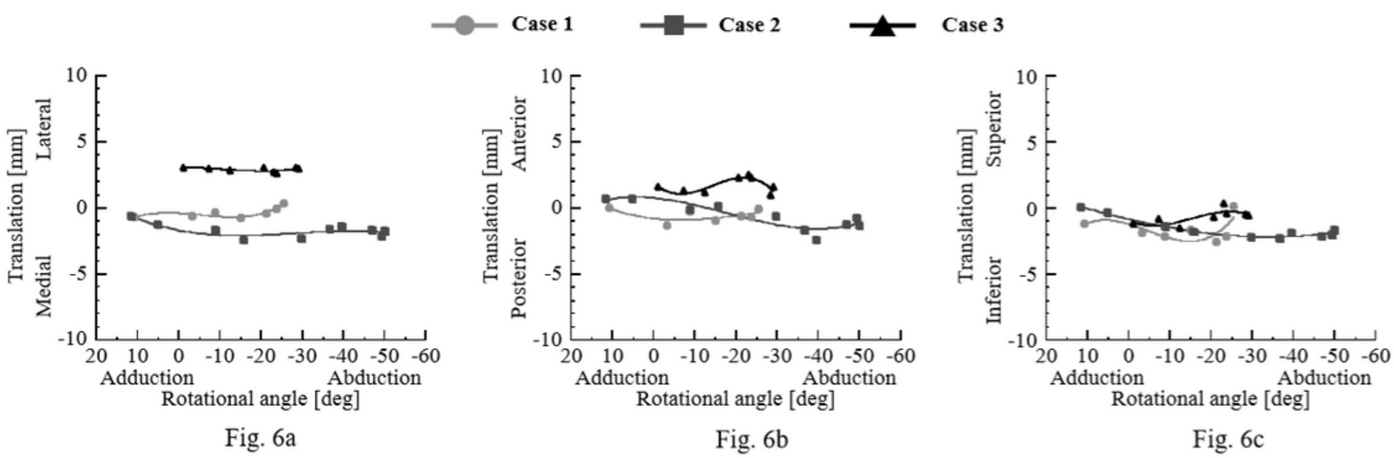

Figure 4

In patients who did not undergo PAO because 6 months of nonsurgical management resulted in reduced pain, dynamic instability of the hip joint is shown on the coronal plane (Fig. 6a), the axial plane (Fig. 6b), and the sagittal plane (Fig. 6c).

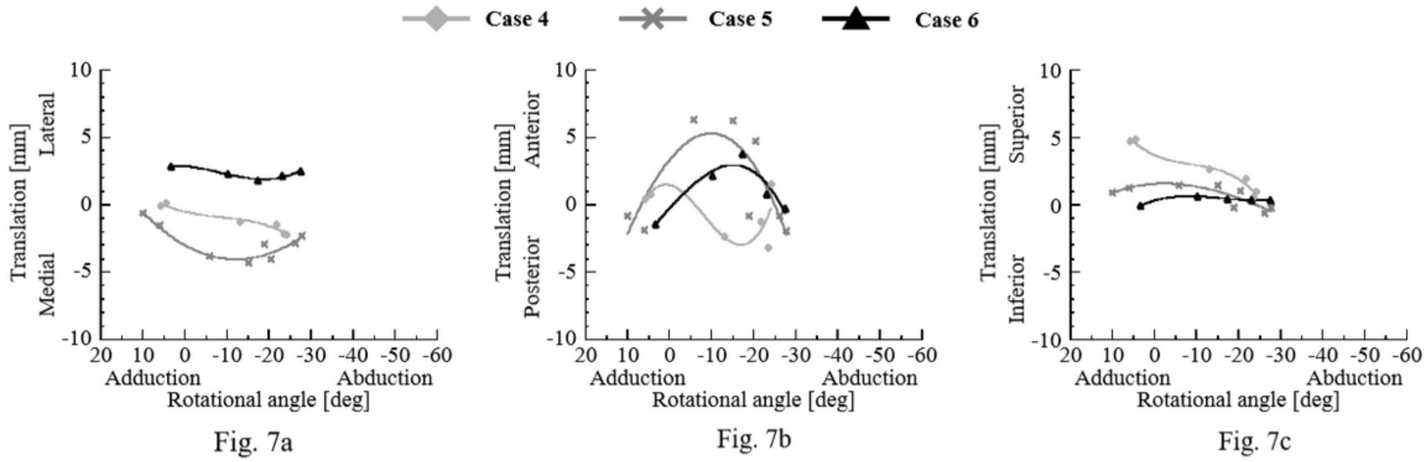

Figure 5

In the patients who underwent PAO due to persistent pain after 6 months of nonsurgical management, dynamic instability of the hip joint is shown on the coronal plane (Fig. 7a), the axial plane (Fig. 7b), and the sagittal plane (Fig. 7c).