Biomechanical Study on the Efficacy of the Periacetabular Osteotomy using Patient-specific Finite Element Analysis

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Periacetabular osteotomy (PAO) is a joint-preserving surgical procedure and it has been introduced as a surgical alternative to the total hip arthroplasty (THA) for young person. However, its clinical and biomechanical efficacies remain unknown. In this study, we constructed patient-specific finite element (FE) models of the hip joint before and after surgery to evaluate the efficacies in more quantitative fashion. 3-D FE models were constructed based on patient’s computed tomography (CT) images. Post-operative geometrical changes in joint contact areas, center-edge (CE) angle and distance between the symphysis pubis and the femoral head (DBSPFH) were assessed in three dimensions. In addition, changes in peak contact pressures and peak von Mises stress (PVMS) at the hip joint were predicted. After PAO, CE angle was increased by 126.2% and DBSPFH was decreased by 3.7%. The contact area was increased by 32% while peak contact pressure was decreased by 53.8%. More even distribution of stresses at the femur were observed. Our results suggested that for this given patient PAO was an effective reconstructive surgical choice in terms of reconstructing joint congruency. Therefore, PAO can be considered a good alternative to THA especially for young patients who need to be treated with joint-preserving techniques.

1. Introduction

Developmental dysplasia of the hip (DDH) presents with multiple morphological features including acetabular dysplasia, decreased acetabular coverage of the femoral head, excessive femoral anteverision, increased neck-shaft angle, and a shortened femoral neck. These morphological abnormalities may result in intensified joint loading at certain locations of the hip articulating surfaces and eventually lead to degradation of the articular cartilage. Most patients with DDH are adolescents and younger adults with congenital deformities. When left untreated, DDH can cause secondary osteoarthritis (OA) at an early age. PAO was introduced by Ganz in 1984 and has been regarded as an effective reconstructive osteotomy method to treat DDH in adolescents and younger adults. The osteotomy is performed at the periphery of the ilium and the ischium and followed by rotation of the acetabulum. Three-dimensional alignment between the femoral head and the acetabulum can be achieved for optimal congruency of the joint interface using fluoroscopy. Due to its capability of restoring normal hip joint contact in three dimensions, PAO has been recognized as one of the optimal treatment modalities for DDH. Clinical studies suggest that PAO can reduce upper exterior acetabulum inclination, increase the femoral head working range, reduce joint load, and increase the femoral head-acetabulum contact area. Biomechanical findings show PAO is able to induce decrease in joint loading and resulting adductor muscle force through the medial translation of the hip joint center.
Clinical assessment of patient outcome after PAO is usually made from 2-D measurement of parameters on antero-posterior (AP) radiographs or computed tomography (CT) of the patient before and after surgery. The parameters include the center-edge (CE) angle on AP radiographs which is formed by a vertical line drawn from the center of the femoral head at right angle to the line joining the femoral head center, and a line from the center of the femoral head to the lateral edge of the acetabular roof. From the axial CT images of the hip joint the acetabular sector angles is used for clinical assessment as it provides information on the area of the femoral head covered by the acetabulum. However, these parameters often fall short of suggesting true outcome whether the contact area between the femoral head and the acetabulum has been increased and the joint stress has been reduced.

Biomechanical studies on the efficacy of the PAO are fairly limited. Only a few in vitro experimental studies have been reported. These studies investigated changes in contact pressure at the hip joint interface of either composite or cadaveric bones using pressure films. These in vitro experimental studies were able to provide baseline values of the hip joint contact pressure, however, measured data were inherently limited to detectable size and range of the pressure film. These studies also had specimen-to-specimen variation. Thus, computational analysis such as finite element (FE) method is an attractive alternative to experimental testing method since it is capable of predicting joint contact area and resulting stresses before and after surgery. Especially with patient-specific FE analysis efficacy of PAO can be assessed more quantitatively for a particular individual based on his/her pre/post-operative CT image data. Various surgical parameters involved in PAO can be better understood in terms of hip contact mechanics and improvements in the diagnosis and treatment of the hip deformities can be made.

In this study, we constructed patient-specific FE models of the hip joint before and after surgery to evaluate the clinical efficacies of the PAO in more quantitative fashion. Post-operative geometrical changes in joint contact areas, CE angle and distance between the symphysis pubis and the femoral head (DBSPFH) were assessed in three dimensions. In addition, changes in peak contact pressures and peak von Mises stress (PVMS) at the interface between the acetabulum and the femoral head due to surgery were predicted.

2. Materials and Methods

2.1 Three-dimensional patient-specific hip models

A pre-operative 3-D FE model of a hip of the patient (female, 42 years old, 52 kg) was constructed as follows. First, to reconstruct a patient-specific 3-D FE model, two dimensional CT scan images (2-mm thick, 0.398 mm pixel width, Aquilion 64, Toshiba Medical System Corp., Japan) of the hip and the pelvis of the patient suffering from DDH were obtained, as shown in Fig. 1(a). Second, the CT images were imported to an image-processing software (Mimics v14.1, Materialise, Louvain, Belgium), and were then changed to DICOM format to meet compatibility requirement of the software. Bone tissues were differentiated from soft tissues in relation to the threshold in grey scale value (1,262 - 2,994 in 12-bit grey scale) that is equivalent of 226 - 3,017 HU (Hounsfield Units). Furthermore, subdivision between the cortical and cancellous bones of the proximal femur was made based on the threshold value for the cortical bone (662 to 1,988 HU). Smoothing and refining routines were applied to eliminate any noise that might have been left previously. More specifically, “the masks” comprised of a group of pixels that falls within the appropriate range of HU for bones were applied to filter out the noise, as shown in Fig. 1(b). Then, 2-D images were transformed to reconstruct surface-based 3-D geometry of the hip and the pelvis by stacking up each 2-D images. The length of the proximal femur model was 180 mm as measured from the most superior point on the femoral head to the middle of the femoral shaft. Third, the outer contours of the pelvis and the proximal femur were extracted and manual segmentation was followed using a computer aided design (CAD) program (Rhinoceros 3.0, Robert McNeel & Associates Corp., WA, USA) to connect the outer contour, as shown in Fig. 1(c). Finally, solid modeling and mesh generation were carried out with a pre-processing program (Patran 2006, MSC Software Corp., CA, USA), as shown in Fig. 1(d).

Hexahedral solids were used to fill its volume for more precise loading response particularly for the proximal femur. Automatic meshing was done for both the femur and the pelvis, as shown in Fig. 2(a). As the boundary between the cartilage and the bone was not clearly identifiable from the CT images, it was assumed that the joint interface surfaces between the femoral head and the acetabulum were covered uniformly with articular cartilage of 1-mm thickness that was modeled with eight-node hexahedral solids. Material properties for the cortical bone, the cancellous bone, and the cartilage were obtained from the literature, as described in Table 1.

The post-operative FE model was constructed based on the post-operative CT scan images which was obtained 2 months after PAO of the same patient following the exact same procedures as in the case of the pre-operative FE model, as shown in Fig. 2(c). The post-op CT images reflect the surgical outcome of PAO during which a first incision of the pelvis is made at the ilium proximal to the antero-inferior iliac spine and is continued to the distal part of the quadrilateral surface in a c-shaped curved line (the first osteotomy line), and then another osteotomy was made at the superior ramus of the pubis to separate the acetabulum from the pelvis. Then, the osteotomized acetabulum was rotated anteriorly with respective to the x-axis and laterally (i.e., clockwise rotation) with respect to the y-axis, as shown