**Biomechanical Validation of Computer Assisted Planning of
Periacetabular Osteotomy: A Preliminary Study based on Finite Element
Analysis**

L. Liu¹, T. Ecker², L. Xie³, S. Schumann¹, K. Siebenrock², G. Zheng¹

¹Institute for Surgical Technology and Biomechanics, University of Bern, Bern, Switzerland

² Orthopaedic Department, Inselspital, University of Bern, Bern, Switzerland

³ Med-X Research Institute, Shanghai Jiao Tong University, Shanghai, China

Address for Correspondence:

Prof. Dr. Guoyan Zheng
University of Bern, Institute for Surgical Technology and Biomechanics
Stauffacherstr. 78
CH-3014 Bern, Switzerland
Phone: +41 (0)31 631 5956
Fax: +41 (0)31 631 5960
e-mail: guoyan.zheng@istb.unibe.ch

Total word count: 3390 words

Abstract

Periacetabular Osteotomy (PAO) is a joint preserving surgical intervention intended to increase femoral head coverage and thereby to improve stability in young patients with hip dysplasia. Previously, we developed a CT-based, computer-assisted program for PAO diagnosis and planning, which allows for quantifying the 3D acetabular morphology with parameters such as acetabular version, inclination, lateral center edge (LCE) angle and femoral head coverage ratio (CO). In order to verify the hypothesis that our morphology-based planning strategy can improve biomechanical characteristics of dysplastic hips, we developed a 3D finite element model based on patient-specific geometry to predict cartilage contact stress change before and after morphology-based planning. Our experimental results demonstrated that the morphology-based planning strategy could reduce cartilage contact pressures and at the same time increase contact areas. In conclusion, our computer-assisted system is an efficient tool for PAO planning.

Key words: Periacetabular Osteotomy, Computer-Assisted Diagnosis and Planning, Hip Joint Morphology, Finite Element Analysis.

1. Introduction

Periacetabular osteotomy (PAO) is an effective approach for surgical treatment of hip dysplasia in young adults [1]. The aim of PAO is to increase acetabular coverage of the femoral head and to reduce contact pressures by realigning the hip joint [2]. It was reported [4, 14] that PAO planning is mainly based on two types of optimization strategies which are morphology-based and biomechanics-based optimization, respectively.

Both 2D and 3D images are used in morphology-based planning of PAO surgeries. Clohisy et al. [3] reported to use important features of the hip identified by hip specialists on plain radiographs for diagnosis of pathological hips. As it is known that one dimensional information is missing with X-ray imaging due to the nature of projection, CT is used as a more accurate and informative way of analyzing the morphology of the hip. Klaue et al. [14] proposed a 3D evaluation method estimating coverage and congruency of hip joint from the cross section images of CT scan. More recently, Dandachli et al. [15] described a new CT-based evaluation method for dysplastic hip from the weight bearing surface point of view.

The other type of planning strategy is based on biomechanical optimization. Armand et al. [4] introduced a computer-assisted Biomechanical Guidance System (BGS) combining geometric and biomechanical feedback with intraoperative tracking to guide the surgeon. The PAO planning module computes contact pressures via Discrete Element Analysis (DEA) to suggest a reposition that minimizes peak contact pressure in sitting, standing, and walking positions [5]. Recently, Zou et al. [6] developed a 3D FE simulation of PAO and validated their method on 5 models generated from CT scans of dysplastic hips. The acetabulum of each model was rotated by 5° increments in the coronal plane, and the relationship between contact area and Von Mises stress in the femoral and acetabular cartilage was investigated until the optimal position for the acetabulum was found.

Previously, we have developed a computer-assisted planning system for PAO, which allows for not only quantifying the 3D hip morphology with parameters such as acetabular inclination, version, LCE angle and coverage (CO) for a computer-assisted diagnosis of hip dysplasia but also virtual PAO surgical planning and computer assisted interventions [16]. This paper expands on [16] with a 3D FE model to verify the hypothesis that our morphology-based planning strategy can improve biomechanical characteristics of dysplastic hips.

2. Materials and Methods

2.1. Computer-Assisted Planning and Navigation System for PAO

The workflow of the computer-assisted planning and navigation of PAO is shown in Fig. 1. Our system works in two stages: preoperative planning stage and intraoperative navigation stage. The input to the preoperative planning stage is 3D surface models of pelvis and femur segmented from CT data. The pelvic local coordinate systems (see Fig. 1(A)) is then established on the anterior pelvic plane (APP) defined by the bilateral anterior superior iliac spines (ASISs) and the bilateral pubic tubercles [7]. Subsequently, a fully automatic detection of the acetabular rim is conducted. The detected acetabular rims allow for quantifying the acetabular morphology with parameters such as inclination, version, LCE and femoral head coverage (Details about all the morphological parameters can be found in the supplementary material.). After that, virtual reorientation procedure for acetabulum fragment is performed by interactively adjusting inclination and version angles of the acetabular fragment until morphological parameters of normal hip are obtained ($50.7^{\circ} < \text{inclination} < 66.8^{\circ}$ [21], $14.0^{\circ} < \text{version} < 33.3^{\circ}$ [21], $\text{LCE} > 25^{\circ}$ [6]) (see Fig. 1(B)). In order to avoid impingement following PAO, the planned situation is optimized with impingement simulation by balancing acetabular coverage with hip range of motion (ROM) [16]. The results from the planning

stage (Fig. 1(C)) can be passed to the intraoperative navigation stage (Fig. 1(D)) where a visual feedback is provided during the acetabular fragment reorientation procedure in order to achieve the planned situation [17].

2.2. Biomechanical Model Based on Patient-specific Geometry

Mesh Generation

After virtual reorientation planning, the bone surface model of the realigned hip joint was stored as a STL file and then imported into ScanIP software (Simpleware Ltd, Exeter, UK) (Fig. 2(A) and (C)). While patient-specific cartilage models are essential in biomechanical simulation, it has been previously reported in [8] that the predicted optimal alignment of the acetabulum was not sensitive to the choice of cartilage thickness distribution over the acetabulum. Therefore a 3D dilation operation was performed on femoral head and lunate surface of acetabulum to create femoral and acetabular cartilage layers with a constant thickness (1.8mm) following the principle introduced in [6]. Surfaces were then discretized using tetrahedral elements (Fig. 2(B) and (D)). Since the primary concern was focused on the joint contact, a finer mesh was employed for the cartilage than for the bone. Refined tetrahedral meshes were constructed for the cartilage layers using ScanFE module (Simpleware Ltd, Exeter, UK). Cortical bone surfaces were discretized using coarse tetrahedral elements. Trabecular bone was not included in the models, as it only has a minor effect on the predictions of contact stress as reported in [9].

Material property

Acetabular and femoral cartilages were modeled as homogeneous, isotropic, and linearly elastic material with Young's Modulus $E=15$ MPa and Poisson's ratio $\nu=0.45$ as reported in

[6]. Cortical bone of pelvis and femur were modeled as homogeneous, isotropic material with elastic modulus $E=17$ GPa and Poisson's ratio $\nu=0.3$ as suggested in [6].

Boundary Conditions and Loading

Tied and sliding contact constraints were used in Abaqus/CAE 6.10 (Dassault Systèmes Simulia Corp, USA) to define the cartilage-to-bone and cartilage-to-cartilage interfaces, respectively. It has been reported in [18] that the friction coefficient between articulating cartilage surfaces was very low (0.01–0.02 in the presence of synovial fluid) [10]. Therefore, it is reasonable to neglect frictional shear stresses between contacting articular surfaces.

The boundary conditions used in this paper resembled those used by Phillips et al. [12] (Fig. 2 (E)). The top surface of pelvis and pubic areas were fixed, and the distal end of the femur was constrained to prevent displacement in the body x and y directions while being free in vertical z direction (Fig. 2 (E)). The center of femoral head derived from a least-squares sphere fitting was selected to be the reference node. The nodes of femoral head surface were constrained by the reference node via kinematic coupling.

The fixed boundary condition model was then subjected to a loading condition as published in [12], representing a single leg stance situation with the resultant hip joint contact force acting at the reference node. The resultant force was applied based on anatomical coordinate system described in Bergmann et al [11], and the components of contact force along 3 axes were given as 195N, 92N, and 1490N, respectively, by assuming a constant body weight of 650N for all subjects to remove any scaling effect of body weight on the absolute value of the contact pressure.

Mesh Sensitivity Study and Model Validation

In order to test the sensitivity of our model to the mesh resolution, we conducted a study on two subjects with three different resolutions: coarse, fine and very fine. For example, the numbers of cartilage elements for the 1st subject were 129,290 for the coarse resolution, 221,958 for the fine resolution and 546,841 for the very fine resolution, respectively. We finally select the fine resolution to model cartilage because the differences of the predicted peak contact pressure and contact area are smaller than 1% between the fine and the very fine resolution while the differences of the predicted peak contact pressure and contact area between the coarse and the fine resolutions are greater than 2%.

The models were validated by comparing the predicted contact pressures and areas in hips after reorientation with those of normal hips measured by in vitro experimental studies. Adams et al. [22] found peak contact pressures using pressure transducers ranging from 5.26 to 8.57 MPa during normal walking loads comparable to the peak pressures (4.9 ± 1.1 MPa) of the reoriented hips. Brown et al. [23] measured contact areas of around 1500mm^2 comparable to the contact area ($1168.3 \pm 320.1\text{mm}^2$) of the reoriented hips. However, uncertainty and inconsistency regarding the magnitude of the applied load or body weight make it difficult to compare results directly. Regardless, since the contact pressures and areas predicted by our FE model did fall within the range of the aforementioned experimental values, our FE model is in fair agreement with in vitro measurements.

3. Study Design and Results

The purpose of our study is to investigate the change of cartilage contact stress before and after a computer-assisted planning of PAO based on a 3D FE simulation. The study was conducted on CT scans of four patients with hip dysplasia. We quantitatively compared the predicted peak contact pressure and contact area on acetabulum cartilage between the original and the reoriented acetabulum positions in order to investigate whether the contact pressure

pattern on acetabular cartilage could be improved with our morphology-based PAO planning. After reorientation planning, hip morphological parameters fall within the range of "normal" values (inclination: $50.2 \pm 2.4^\circ$, version: $16.6 \pm 6.4^\circ$, LCE: $27.0 \pm 1.7^\circ$, CO: $62.8 \pm 4.1\%$). It was found that the CO from the reoriented acetabulum was increased by $10.2 \pm 2.0\%$ when comparing to that obtained from the originally dysplastic acetabulum (Table 1). A statistically significant improvement was found with a paired Student t-test (CO: $p < 0.05$; LCE: $p < 0.05$). The peak contact pressure was reduced from $10.1 \pm 6.1 \text{ MPa}$ to $4.9 \pm 1.1 \text{ MPa}$, and simultaneously the contact area was increased from $723.5 \pm 227.3 \text{ mm}^2$ to $1168.3 \pm 320.1 \text{ mm}^2$. It is noticed that the peak contact pressure of the 3rd subject remains extremely high. This is due to the fact that this patient possesses severely dysplastic hip (LCE is only 7.7°) (Table 1). The contact pressure distribution of this patient before reorientation concentrates on the superior region with a small contact area. After reorientation, the contact area is enlarged significantly (Fig. 3).

4. Discussion

It is known that the purpose of PAO is to increase acetabular coverage of the femoral head and thereby decrease contact pressure over the cartilage surface [2], but a limitation common to all these previously work [3,14,15] is that they only provide a pure morphology-based assessment and/or planning without considering the biomechanical effect of the reorientation planning. This has motivated the recent introduction of various systems based on biomechanics optimization [4-6]. The BGS introduced by Armand et al. [4] performed computationally efficient DEA to estimate the contact pressure. In contrast, we developed a 3D FE model for biomechanical analysis of our morphology-based planning results. Although CT scan was performed in the supine position and the loading condition of FE model is one-leg stance [11], Niknafs et al. [8] has shown no significant difference between the contact pressure in the one-leg stance reference frame and those in the supine reference

frame. Additionally, as pointed out by Armiger et al. [5], it is not an infrequent clinical practice to use models derived from the supine frame to do biomechanical simulation of the standing frame. Therefore we believe our model makes good use of valuable, available data from the original Bergmann's work [11].

The experimental results that we obtained are consistent with those reported by Zou et al. [6]. More specifically, both studies confirm the clinical observation that acetabulum reorientation in PAO will lead to reduced cartilage contact pressure and increased contact area. However, different from the strategy used by Zou et al. [6] who developed a 3D FE simulation based optimal reorientation planning method without considering the possible reduction of hip ROM caused by the planned reorientation position, we developed a computer assisted PAO planning system with impingement simulation to balance acetabular coverage with hip ROM [16]. Thus, the planned reorientation position obtained from our system will not only reduce the cartilage contact pressure and increase the contact area, but also have a balanced hip ROM, which is important to avoid any potential femoroacetabular impingement (FAI) after PAO surgery as reported in our previous work [16].

It is worth to mention the limitations of the present method. The main limitation is that the acetabular labrum was neglected in our FE models of dysplastic hips due to the fact that labrum cannot be delineated from conventional CT data. Although the role of the labrum in modeling hip load distribution is controversial in the literature [19, 20], it is now commonly agreed that it is important to include the labrum in hip biomechanical models [19]. Another limitation is on the cartilage models used in our study. Without injecting a contrast agency, we cannot delineate cartilage from a CT data. Thus, we choose to create cartilage models following the principle introduced in [6]. The influence of using such a cartilage model on hip load distribution needs to be further investigated. The last limitation is that a fixed body weight of 650 N derived from Bergmann et al. [11] was applied to all 4 dysplastic hips for FE

simulation, which is not patient-specific. The argument why we adopt such a strategy is that we are aiming to compare the relative change of contact pressure before and after PAO reorientation planning. Thus, it makes sense to use a constant loading, which was originally proposed by Zou et al. [6].

In summary, the preliminary FE study confirmed that the acetabular reorientation position obtained from our morphology-based PAO planning system would lead to a reduced contact pressure and an increased contact area. Together with the navigation solution [17], we offered a complete solution for PAO interventions, ranging from computer-assisted diagnosis of hip dysplasia, preoperative PAO reorientation planning, to intraoperative navigation of PAO surgery.

5. Acknowledgements

This work was partially supported by the Japanese-Swiss Science and Technology Cooperation and the Swiss National Science Foundation (SNF) Short International Visit Grant IZK0Z3_149048.

Conflict of Interest

The authors have no conflict of interest related to this work.

Appendix A: Supplementary material

Competing interests: None declared

Funding: the Japanese-Swiss Science and Technology Cooperation and the Swiss National Science Foundation (SNF) Short International Visit Grant IZK0Z3_149048.

Ethical approval: Not required

References

1. Murphy SB, Millis MB, Hall JE. Surgical correction of acetabular dysplasia in the adult. A Boston experience. *Clin Orthop Relat Res.* 1999;363:38–44.
2. Iglic A, Iglic VK, Antolic V, Srakar F, Stanic U. Effect of the periacetabular osteotomy on the stress on the human hip joint articular surface. *IEEE Trans. Rehabil. Eng.* 1993;1(4):207–12.
3. Clohisy JC, Carlisle JC, Trousdale R, Kim YJ, Beaulé PE, Morgan P, et al. Radiographic evaluation of the hip has limited reliability. *Clin Orthop Relat Res.* 2009;467(3): 666–75.
4. Armand M, Lepistö JVS, Taylor RH, et al. Computer-aided orthopedic surgery with near-real-time biomechanical feedback. *Johns Hopkins APL Technical Digest.* 2004;25(3):242–52.
5. Armiger RS, Armand M, et al. Three-dimensional mechanical evaluation of joint contact pressure in 12 periacetabular osteotomy patients with 10-year follow-up. *Acta Orthop.* 2009;80(2):155–61.
6. Zou Z, Chavez-Arreola A, et al. Optimization of the position of the acetabulum in a Ganz periacetabular osteotomy by finite element analysis, *J Orthop Res.* 2012;31(3):472–9.
7. Zheng G, Marx A, et al. A hybrid CT-free navigation system for total hip arthroplasty. *Comput Aided Surg.* 2002;7(3):129–45.
8. Niknafs N, Murphy RJ, Armiger RS, Lepistö J, Armand M. Biomechanical factors in planning of periacetabular osteotomy. *Biomechanics.* 2013;1(20):1–10.
9. Anderson AE, Ellis BJ, Maas SA, Peters CL, Weiss JA. Validation of finite element predictions of cartilage contact pressure in the human hip joint. *J Biomech Eng.* 2008;130(5):051008.

10. Caligaris M, Ateshian GA. Effects of sustained interstitial fluid pressurization under migrating contact area, and boundary lubrication by synovial fluid, on cartilage friction. *Osteoarthr. Cartil.* 2008;16(10): 1220–7.
11. Bergmann G, Deuretzbacher G, et al. Hip contact forces and gait patterns from routine activities. *J Biomech.* 2001;34:859–71. Including the HIP98 CD, 3-9807848-0-0.
12. Phillips ATM, Pankaj P, Howie CR, Usmani AS, Simps AHRW. Finite element modelling of the pelvis: Inclusion of muscular and ligamentous boundary conditions. *Med Eng Phys.* 2007;29:739–48.
13. Puls M, Ecker TM, et al., Automated detection of the osseous acetabular rim using three-dimensional models of the pelvis. *Comput Biol Med.* 2011;41(5):285–91.
14. Klaue K, Wallin A, Ganz R. CT evaluation of coverage and congruency of the hip prior to osteotomy. *Clin Orthop Relat Res.* 1988;232:15–25.
15. Dandachli W, Kannan V, et al. Analysis of cover of the femoral head in normal and dysplastic hips: new CT-based technique. *J Bone Joint Surg Br.* 2008;90(11):1428–34.
16. Liu L, Ecker TM, Schumann S, Siebenrock KA, Nolte LP, Zheng G. Computer assisted planning and navigation of periacetabular osteotomy with range of motion optimization. *Medical Image Computing and Computer-Assisted Intervention–MICCAI 2014.* Springer International Publishing. 2014; 643–650
17. Liu L, Ecker TM, Schumann S, Siebenrock KA, Nolte LP, Zheng G. A novel planning and navigation system for periacetabular osteotomy (PAO). *International Journal of Computer Assisted Radiology and Surgery*, 2014;9(Suppl 1):S168–9.
18. Harris MD, Anderson AE, et al.. Finite element prediction of cartilage contact stresses in normal human hips. *J Orthop Res.* 2012;30(7), 1133–9.

19. Henak CR, Abraham CL, et al. Patient-specific analysis of cartilage and labrum mechanics in human hips with acetabular dysplasia. *Osteoarthr. Cartil.* 2014;22(2), 210–7.
20. Konrath GA, Hamel AJ, Olson SA, Bay B, Sharkey NA. The Role of the acetabular labrum and the transverse acetabular ligament in load transmission in the hip. *J Bone Joint Surg Am.* 1998;80(12), 1781–8.
21. Murtha PE, Hafez MA, Jaramaz B, DiGioia AM. Variations in acetabular anatomy with reference to total hip replacement. *J Bone Joint Surg Br.* 2008;90(3), 308–313.
22. Adams D, Swanson SA. Direct measurement of local pressures in the cadaveric human hip joint during simulated level walking. *Annals of the rheumatic diseases.* 1985; 44(10), 658–666.
23. Brown TD, Shaw DT. In vitro contact stress distributions in the natural human hip. *J Biomech.* 1983;16(6), 373–384.

Table 1 The hip joint morphological parameters and cartilage contact stress change in static loading condition before and after reorientation planning.

Before reorientation planning					
Case	01	02	03	04	Average
Inclination (°)	62.7	60.7	69.3	59.9	63.2±4.3
Version (°)	31.1	20.2	12.8	15.4	19.9±8.1
LCE (°)	22.5	15.5	7.7	15.6	15.3±6.0
CO (%)	54.8	48.9	52.8	53.7	52.6±2.6
Peak pressure (MPa)	9.7	5.5	18.9	6.3	10.1±6.1
Contact area (mm²)	580.2	806.1	503.0	1004.6	723.5±227.3
After reorientation planning					
Case	01	02	03	04	Average
Inclination (°)	50.7	48.7	53.3	47.9	50.2±2.4
Version (°)	26.1	15.2	12.8	12.4	16.6±6.4
LCE (°)	28.6	26.2	25.1	28.2	27.0±1.7
CO (%)	65.7	56.9	65.5	63.0	62.8±4.1
Peak pressure (MPa)	6.3	3.8	5.2	4.1	4.9±1.1
Contact area (mm²)	833.9	1496.7	961.9	1380.6	1168.3±320.1

List of Figures

Fig. 1 Schematic view of computer-assisted planning and navigation of PAO. (A) the input surface models and the pelvic local coordinate system on the anterior pelvic plane (APP) defined by both anterior superior iliac spines (ASIS) and the mid-point of the pubic tubercles (T). The hip center (H) is extracted by least-squares sphere fitting of femoral head surface; (B) computer-assisted PAO planning with range of motion optimization; (C) preoperative planning output; (D) intraoperative PAO navigation.

Fig. 2 Biomechanical simulation of contact pressure on acetabular cartilage. (A) surface models of a dysplastic hip; (B) volume meshes of a dysplastic hip; (C) surface models for a planned situation after acetabulum fragment reorientation; (D) volume meshes for the planned situation; (E) boundary conditions and loading for biomechanical simulation; (F) coarse meshes for pelvic and femoral models, and refined meshes for pelvic and femoral cartilages.

Fig. 3 Contact pressures on acetabular cartilage in static one-leg stance scenario. (A) contact pressure distributions for the original dysplastic hips where the 3rd subject who suffered severe dysplasia (LCE: 7.7°); (B) contact pressure distributions after reorientation planning.

Figure-1

Pre-operative Planning Stage

Intra-operative Navigation Stage

Figure-2

Figure-3