Computer Aided Design and Evaluation of New Anatomic Fixation System on Entire Pelvic Model

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ABSTRACT

This paper presented a special computer aided procedure to design a new sacroliliac anatomic bar-plate internal fixation system, and evaluated its biomechanical properties on an accurate patient-specific finite element model of entire pelvis, compared with two conventional internal fixation methods. Based on virtual anatomical measure of 30 digital pelvic models reconstructed from CT, an anatomic plate was designed according to the complicated structure of the outer table of the posterior ilium, and was integrated into the complete fixation system. Then, an ad hoc semi-automatic mesh generator was employed to construct a patient-specific finite element model of whole pelvis, including elaborate sacroiliac joints, important pelvic ligaments, and interpubic disc, as well as position-dependent cortical thickness and trabecular bone elastic modulus. Following, one side of sacroiliac joint related ligaments were deleted to simulate a complete unilateral sacroiliac joint disruption. Then the new anatomic fixation system was integrated to fix the fracture, and two comparing models including iliosacral screw fixation and front reconstruction plate fixation were also generated. Finally, all models were simulated under same loading conditions. The results demonstrated that the mechanical stability of the new anatomic fixation system was superior, with obviously improved stress distribution and little displacement, which implied an effective internal fixation method for potential clinical application.

Categories and Subject Descriptors

J.6 [**Computer Applications**]: COMPUTER-AIDED ENGINEERING – *Computer-aided design (CAD)*; I.3.5 [**COMPUTER GRAPHICS**]: Computational Geometry and Object Modeling – *Physically based modeling*.

General Terms

Design, Performance, Reliability.

Keywords

Computer aided design; Finite element modeling; Pelvis; Sacroiliac joint fracture.

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1. INTRODUCTION

The pelvis is one of the most important components of the musculoskeletal system, consisting of two hip bones and one sacrum, which are connected by a pair of sacroiliac joints and the pubic symphysis. These three bones and three joints form a closed osteo-articular ring combined with strong accessory ligaments. The closed ring makes the structure of the pelvis unique, and the movement of each sacroiliac joint is dependent on the other one. However, this optimized structure, especially the sacroiliac joint, is very sensitive to fractures and disruptions of ligaments, which usually imply important instabilities [1].

Many different treatments have been employed, such as external and internal fixations. Although internal fixation is more aggressive, fewer complications arise over the long term [1]. On the other hand, with the development and popularization of minimally invasive surgical methods and implants for fracture fixation, it is increasingly important that the available implants are precontoured to the specific anatomic location for which they are designed. For example, anatomic plates for clavicular, tibia, and posterior lumbar have been invented to improve the treatments [2-4]. Whereas the complexities of these anatomic locations are much moderate compared with the sacroiliac complex involved in this paper. To the best of the authors' knowledge, there is no published study that develops an anatomic plate for the pelvis in the biomedicine and biomechanics fields.

This paper presented a special computer aided procedure to design a new sacroliliac anatomic bar-plate internal fixation system (SABP). To evaluate the mechanical stability, an ad hoc semi-automatic mesh generator was employed to construct an accurate finite element (FE) model of entire pelvis, based on which the new SABP system was integrated to simulate the pelvic fracture fixation, compared with two conventional internal fixation methods: iliosacral screw fixation, and front reconstruction plate fixation.

2. SYSTEM DESIGN AND SIMULATION

2.1 Sacroliliac Anatomic Bar-plate Internal Fixation System

The whole design of SABP system comprises a posterior supporting bar connected directly with an anatomic plate on the outer table of posterior ilium, two posterior sacral screws and axial connectors, and up to eight optional plate accessory short pedicle screws, as illustrated in Fig. 1.

The posterior supporting bar can be seen as some cut off sacral bar, only drills through one iliac bone on the fracture side, and attached to the sacrum by the two posterior sacral screws with the entry sites at the exterior margins of each processus articularis superior [5]. Those plate screws are used to fasten the anatomic plate and the fractural sacroiliac complex. The joining bar-plate is settled along the main trajectory of stress distribution of posterior pelvis like an arch bridge, which provides immediate three-column stabilization of the pelvis ring.

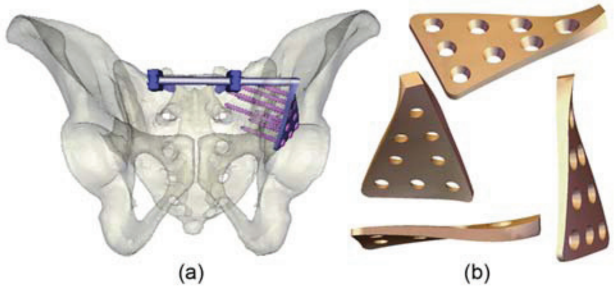

Figure 1. (a) The new sacroliliac anatomic bar-plate internal fixation system. (b) The anatomic plate from different view angles.

The key innovation of the system is the anatomic plate. Commonly used reconstruction plates for pelvis fracture are flat plates, which need skilled manual bending to fit the irregular shape of the outer table of posterior ilium. In addition, the conventional rectangular shape design usually requires all plate screws to be disposed on same straight line position, which is not convenient sometimes to guide the screw into safety zone. In other words, there are two basic clinical requirements to the anatomic plate: first is that the undersurface of the plate is precontoured to the outer table of posterior ilium; second is that the pedicle screws through the plate holes should be guided into the safety zone of sacral bone, not imposing risk to adjacent vascular, visceral, or neural structures. Obviously, we first need to determine a plate location region with appropriate shape on the outer table, e.g., which can be described by conventional CAD model [6].

Our design is inspired by previous morphometric analyses. Jackson et al. [7] pointed out that insertion of rods into the lateral sacral masses would be possible and apparently safe. Xu et al. [8] further determined an approximate triangle projection area of the lateral sacral mass on the outer table of the ilium by Kirschner wires. But it was the projection of the outer-most peripheral edge of the lateral sacral mass. In addition, the coarse approximate area could not be described by CAD model.

Instead, this paper conducted virtual anatomical measure and computer aided design on digital pelvic models reconstructed from 30 randomly selected CT scans of adult Chinese.

For each model, the posterior supporting bar (7 mm in diameter) was placed at the level of L5/S1 interspace like a sacral bar so that the exit hole on the outer table of posterior ilium was located at the intersection of the posterior gluteal line and the outer lip of iliac crest, as demonstrated in Fig. 2. Following, three virtual dissection planes perpendicular to the outer table of posterior ilium were constructed as in Fig. 2(a). Plane 1 was parallel to the inferior border of the outer table. Plane 2 was tangent to the exit hole of supporting bar and passing the posterior inferior iliac spine. Plane 3 was tangent to the exit hole and passing the apex of the greater sciatic notch. Next, plane 1 was shifted up 10 mm to get a bottom transverse cut contour, and was shifted up to the exit hole to get a top transverse contour. Then plane 1 was shifted again to get 4 internal transverse contours, resulting 5 transverse strips so that the height of the lowest strip was half of others. Note that there were 12 key points at the intersections of these 6 transverse contours with 2 oblique contours formed by planes 2 and 3. And another 11 key points were distributed on the internal segments of transverse contours except the top one, so that the length of external sub-segments was half of internal, as depicted in Fig. 2(b). Finally, a local coordinate system was generated by the key points 15, 17and 4, and the coordinates of all these 23 key points were recorded.

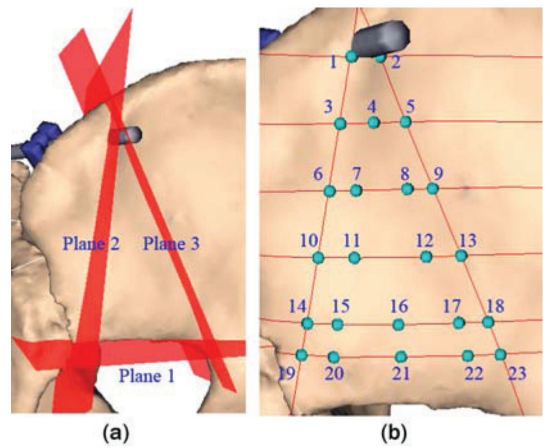

Figure 2. Three virtual dissection planes on the outer table of posterior ilium. (b) Cut contours and 23 key points.

After all individual models were processed, an average distance between the key point 15 and 17 was computed, and all local coordinate systems were scaled to make the same distance. At last, the average statistical coordinates of these 23 key points were acquired, and were used to generate a CAD Spline surface as the undersurface of the anatomic plate.

Afterwards, the algorithm constructed the top and side surfaces of the anatomic plate by normal direction offsetting these 23 key points except the top points 1 and 2, which were moved along the axis direction of supporting bar to obtain a consistent bar-plate joining. And the offset distances decreased linearly from 3.5 mm at top to 1.5 mm at bottom, as shown in Fig. 1(b). Then, eight screw holes were generated at the locations of internal key points, and fillet operations were carried out at the bottom triangle corners. The CAD plate was then joined directly with the supporting bar by Boolean operations, as illustrated in Fig. 1(a).

The remaining outline is now to evaluate the biomechanical properties of the new system. It is difficult to assess the stress and strain distribution throughout the entire pelvis via experiments with cadaveric tissue. An alternative approach is the FEM, which can yields deformation, strain and stress for the entire structure. In addition, this method can easily provide a group of testing models with absolutely the same conditions, which is very important for comparative studies.

2.2 Finite Element Modeling of Entire Pelvis

Although the need for accurate FE models of the entire pelvis in realistic simulation is now becoming more acknowledged, e.g., the biomechanical behavior of a single isolated sacroiliac joint is quite different from its behavior in the intact pelvic ring, modeling of the complete pelvis is not a trivial endeavor, due to its complex 3D structure and geometry, and the mixture of different load bearing parts and material properties. Therefore, most studies were limited to examination of region of interest, such as the acetabulum or one hip bone ([9-11]); or using simplified whole pelvic models ([12-13]), specifically, almost all of these studies oversimplified the sacroiliac complex, and the sacroiliac joint was usually modeled as a part of a rigid structure with no relative motion [14]. But in fact it is a true diarthrodial joint, comprising a joint cavity, two articular surfaces covering nonuniform thickness sacral and iliac articular cartilages supported by subchondral bone end-plates [15].

Using a modified biomechanical semi-automatic mesh generator [16], this paper developed a complete and accurate patient-specific pelvis FE model.

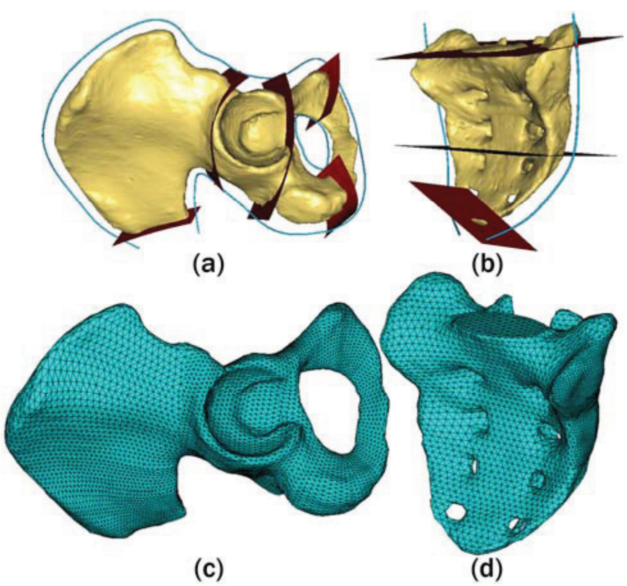

Figure 3. (a-b) The streamline frame curves and key curve cross-section surfaces. (c-d) The resulting FE volumetric meshes of the hip and sacral bone.

First, the individual geometry models of the sacral and hip bones, including the separation surfaces between cortical and trabecular regions, were well reproduced from one selected CT data. It should be noted that this paper limited the thickness of cortical bone in the range of 0.45 mm – 4 mm [10], taking consideration of the fact that CT tends to overestimate the thickness of cortical bone. Then, pairs of streamline frame curves capturing the bone shape feature were generated Fig. 3(a-b). Under the guidance of these curves, sequences of Spline surfaces were interpolated adaptively as cross-sections to construct volumetric meshes of high quality, such as shown in Fig. 3(c-d). The cortical bone was represented with quadratic shell elements, and the trabecular bone was represented by quadratic tetrahedral elements. The average element edge length was 2.8 mm, and the edge length nearby sacroiliac joint was about 1.2 mm.

Then, detailed sacroiliac joints were constructed. According to the measure of McLauchlan al. [15], average sacral articular cartilage is twice as thick as iliac, but the subchondral iliac bone end-plate is 30% thicker than the sacral (0.36 mm vs 0.23 mm). Thus, for each joint, the modeling tool first generated a layer of shell elements with thickness of 0.23 mm as the end-plate on the facies auricularis of sacral bone, and another layer of 0.36 mm for iliac bone; next, constructed the sacral and iliac articular cartilage layers in the thickness proportion of 2:1 by filling the gap with tetrahedral elements, leaving a joint cavity space of 0.5 mm between each other, as shown in Fig. 4(b); then, created surface-to-surface contact with a friction coefficient of 0.15 between the sacral and iliac articular cartilage surfaces. Similarly, the interpubic disc was generated by filling the space between the pubic bones, as depicted in Fig. 4(a).

Finally, several important pelvic ligaments were constructed using Link elements by graphic interaction tools, including interosseous sacroiliac ligament, anterior sacroiliac ligament, posterior sacroiliac ligament, sacrospinous ligament, sacrotuberous ligament, superior pubic ligament, and arcuate pubic ligament, such as those red Link elements shown in Fig. 4, whose attachment points were selected with reference to cadaver specimens as well as standard anatomy atlas.

The employed biomechanical mesh generator [16] has the anisotropic material property assignment function. But there is a lack of published experimental measurements of anisotropic material for pelvic bone, so all pelvic tissues were represented as isotropic elastic in this paper.

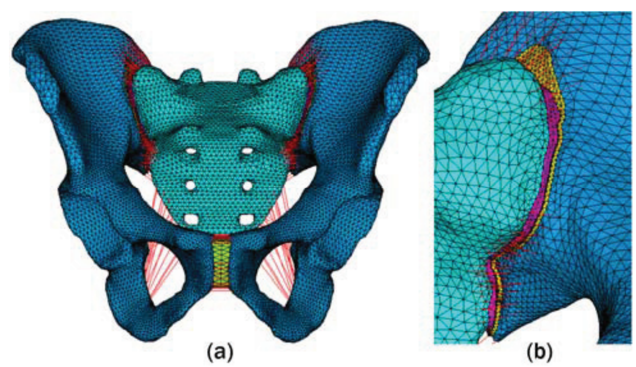

Figure 4. (a) 3D FE model of entire pelvis. (b) Local view of sacroiliac joint region.

For trabecular bone, element-by-element material property assignment was accomplished by finding the number of CT scan pixels lying within each element as well as the gray values [13]. The elastic modulus estimation used the relationship in [10], and Poisson's ratio was taken as 0.2 [9]. Other tissues were all assumed to be homogeneous. The elastic modulus and Poisson's ratio were assigned as follows ([10] [11] [12]): E= 17000 MPa and ν=0.3 for cortical bone; E= 2000 MPa and ν=0.3 for subchondral bone; E= 12 MPa and ν=0.45 for articular cartilage; E= 5 MPa and ν=0.45 for interpubic disc. And the mechanical properties of the pelvic ligaments were listed in Table 1 ([11] [12]).

Table 1. Properties of the pelvic ligaments

Ligament	Stiffness (N/m)	Area (mm2)	Link elements number
Interosseous	800	400	111×2
Anterior sacroiliac	600	120	41×2
Posterior sacroiliac	700	180	49×2
Sacrospinous	415	80	6×2
Sacrotuberous	415	300	14×2
Superior pubic	300	60	10
Arcuate pubic	300	100	15

2.3 Sacroiliac Joint Fracture and Internal Fixation

Afterwards, one side sacroiliac joint related ligaments were deleted to simulate the "worst-case scenario" of complete unilateral sacroiliac joint disruption. Then the SABP system was integrated to fix the fracture, as shown in Fig. 5(a), and comparing treatments using iliosacral screw fixation (IS), and front reconstruction plate fixation (FP), as in Fig. 5(b) and (c), were also generated. The front reconstruction plates used 4 plate screws, and the anatomic plate used 6 out of 8 optional screws (at key points 7, 8, 11, 12, 15, 17). All instruments were assumed to have titanium material property: E= 103000 MPa, ν=0.3.

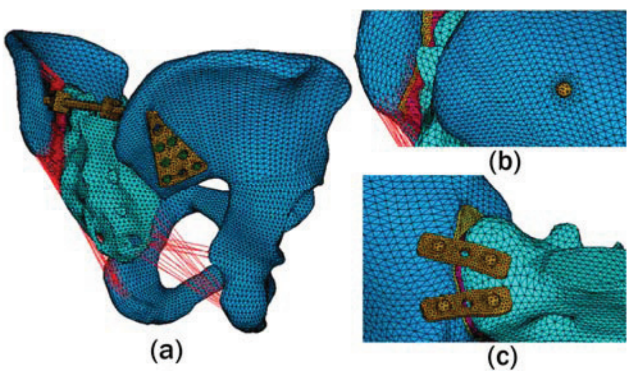

Figure 5. Internal fixations for sacroiliac joint fracture using the new sacroliliac anatomic bar-plate internal fixation system (a), iliosacral screw fixation (b), and front reconstruction plate fixation (c).

The IS model used a S1 pedicle screw of 80 mm long from the outer table of the ilium to the anterior cortex of the sacrum [17]. The FP model employed double reconstruction plates of 45 mm long, which were coarsely bent according to the local anatomic location. In more detail, the modeling tool set an average space of 2 mm between the reconstruction plates and the pelvic surface to imitate the “coarse bending”. In contrast, the SABP model adopted an average space of 0.5 mm between the anatomic plate and the pelvic surface to imitate a “good fit”. Both of them employed surface-to-surface contact with a friction coefficient of 0.1 between the plate and the pelvic surface. All other interfaces between the instruments and bone were considered as perfect unions.

Finally, all five models (including the intact and fracture models), were simulated under same loading conditions: the fixed constraints were applied to the acetabulum regions, and a vertical compression force of 300 N was applied on the base of sacrum.

3. RESULTS

For the new SABP system, the average base width of the triangular anatomic plate is 30 mm, and the triangular height is 56.6 mm. The angles between the supporting bar and two bevel edges of the plate are 83.76° and 100.01°. The undersurface of the plate can match the outer table of posterior ilium of most pelvic sample models without manual bending, with an average inter-space distance less than 0.8 mm. Only 4 test models need further bending, with inter-space large than 2 mm. The plate holes will guide short pedicle screws into the first and second sacral pedicles, avoiding sacral foramens. The average safe length of top screw is 37.5mm (at key point 4), the length of middle screws is 42.3 mm (key points 7, 8, 11, 12), and the length of bottom screws is 31.5 mm (key points 15, 16, 17).

For the internal fixation simulations, this paper compared the peak values of displacement of sacroiliac joints and von Mises stress of several main loading transfer regions in each model. Under the loading of 300 N, the peak displacement value of the sacroiliac joint in the intact pelvic model was 1.69 mm. For the fracture model, the peak displacement was 4.8 mm on the fracture side. For those fixation models, the peak displacement in the FP model was the largest for 1.95 mm; the second was the IS model for 1.89 mm. Both of them were larger than the intact model. In contrast, the peak displacement in the SABP model was only 1.22 mm, decreased about 35% compared to IS fixation, decreased about 37% compared to FP fixation, and was even more stable than the intact model. Fig. 6 illustrated the displacement contour view of the sacral bone in three fixation models.

Using SABP fixation, the peak von Mises stress values of 7 main loading transfer regions were also the smallest, such as shown in Fig. 7. The peak stress in SABP model decreased about 33%-70% compared to IS model in regions of hip cortical and subchondral bone on the fracture side, and decreased about 60%-75% compared to FP model in regions of sacral and hip cortical bone on the fracture side.

4. DISCUSSION AND CONCLUSION

The pelvis is a ring structure, whose stability essentially depends on the integrity of the posterior weight-bearing sacroiliac complex with ligaments. The entire complex has an appearance and structural behavior similar to a suspension bridge, which is very sensitive to fractures and disruptions of ligaments [1]. And various internal fixations, such as sacral bar, iliosacral screw, and front reconstruction plate, are usually recommended for posterior pelvic ring injuries. According to previous biomechanical experiments and FE analysis, each internal fixation technique has its own defects, and some combination treatments could notably improve the pelvis stabilization ([12] [18] [19]).

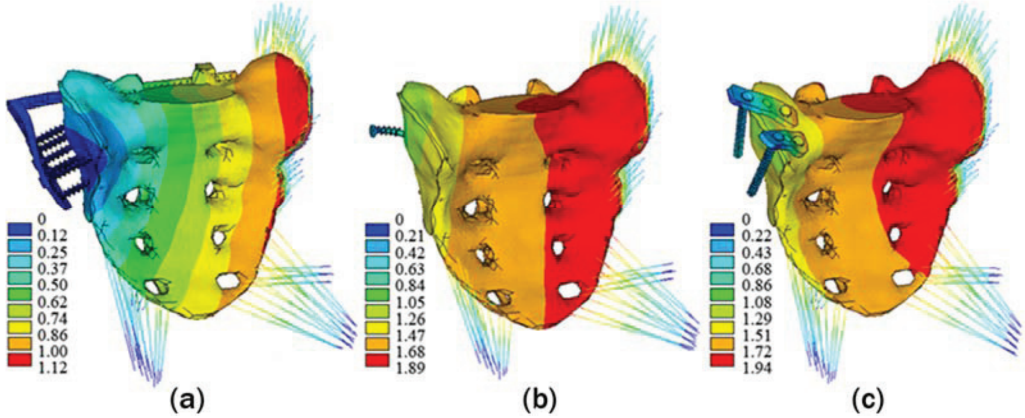

Figure 6. Displacement contour views of the sacral bone in the new sacroliliac anatomic bar-plate internal fixation system (a), iliosacral screw fixation (b), and front reconstruction plate fixation (c), under vertical loading of 500N.

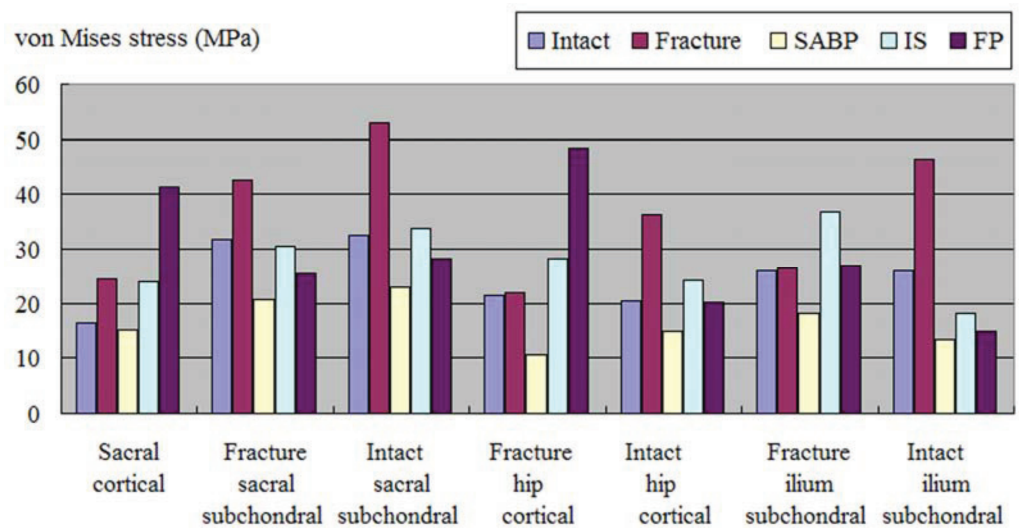

Figure 7. Maximal von Mises Stress of 7 main loading transfer regions under vertical loading of 500N.

Taking advantage of computer aided methodology, this paper has developed a new sacroliliac anatomic bar-plate internal fixation system. The whole system can be seen as some kind of combination of sacral bar, posterior plate and pedicle screws. The bar-plate is settled along the main trajectory of stress distribution of posterior pelvis like an arch bridge, which constitutes a new biomechanical complex with the fractured sacroiliac joint, using two posterior sacral screws and up to eight optional plate pedicle screws. The key innovation is the anatomic plate on the outer table of posterior ilium. Compared with commonly used flat plate, the anatomic plate has many advantages. First, the undersurface of the anatomic plate can fit the irregular shape of the outer table without any manual bending, and provides some "interlock" function. Second, the location of this particular plate on the outer table is explicit and easy to determine, and the shape and size of the plate is complete inside of the projection region of the lateral sacral mass. In addition, based on lots of virtual anatomical measure and testing, the distribution of screw holes on plate can guide pedicle screws into the first and second sacral pedicles safely, avoiding sacral foramens.

As comparisons between the results obtained from FE analysis and those obtained from experimental testing reveal a close correlation ([12] [20]), this paper evaluated the mechanical stability of the SABP system, compared with conventional fixation methods, on an accurate FE model of entire pelvis. FE modeling of the entire pelvis is technically difficult because of its complex anatomic architecture and geometry. Utilizing a modified biomechanical mesh generator, we prepared a whole pelvis FE model with accurate and well structured volumetric mesh, and position-dependent cortical thickness and trabecular bone elastic modulus [10]. And most importantly, the base pelvic model has elaborate sacroiliac joints with accessory ligaments, which is essential for realistic simulation of sacroiliac joint fracture as well as posterior pelvic ring fixations.

Under the same load condition, the simulation results reveal that the mechanical stability of the SABP system is significantly better than conventional internal fixation treatments, with obviously improved stress distribution and little displacement.

We also acknowledge the limitations of our study. First, only static load simulation was conducted in this paper. Although that is appropriate for comparative studies, dynamic cycle load is essential to investigate the fatigue behavior of the new system. Second, the interfaces between the embedding screws and bone were considered a perfect union, which is not completely true. And it is probably the reason that the maximal displacement in the SABP mode was even less than the intact model. In addition, the new system requires further assessment with biomechanical experiment and in vivo testing.

Anyway, the design of the SABP system reflects the trend of anatomic and minimally invasive implant development. And the potential clinical application of the new system for posterior pelvic ring fixation is appealing. Further pre-clinical validations on the new system will be carried out to improve its performance.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Simonian, P. T., Routt, M. L. 1997. Biomechanics of pelvic fixation. Orthopedic Clinics of North America 28, 3 (1997), 351–67.

[2] Huang, J. I., Toogood, P., Chen, M. R., Wilber, J. H., Cooperman, D. R. 2007. Clavicular anatomy and the applicability of precontoured plates. Journal of Bone and Joint Surgery – American 89, 10 (2007), 2260–5.

[3] Schmutz, B., Wullschleger, M. E., Kim, H., Noser, H., Schütz, M. A. 2008. Fit assessment of anatomic plates for the distal medial tibia. Journal of orthopaedic trauma 22, 4 (2008), 258–63.

[4] Ferree, B. A. 2005. Anatomic posterior lumbar plate. U.S. Patent 6843790, 2005.

[5] Xu, R., Ebraheim, N. A., Yeasting, R. A., Wong, F. Y., Jackson, W.T., Mirkovic. S. 1995. Morphometric evaluation of the first sacral vertebra and the projection of its pedicle on the posterior aspect of the sacrum. Spine 20, 8 (1995), 936–40.

[6] Huang, Q.-X., Hu, S.-M. Martin, R. R. 2005. Fast degree elevation and knot insertion for B-spline curves. Computer Aided Geometric Design 22, 2 (2005), 183-97.

[7] Jackson, R. P., McManus, A. C. 1993. The iliac buttress: a computed tomographic study of sacral anatomy. Spine 18, 3 (1993), 1318–28.

[8] Xu, R., Ebraheim, N. A., Douglas, K., Yeasting, R. A. 1996. The projection of the lateral sacral mass on the outer table of the posterior ilium. Spine 21 (1996), 790–5.

[9] Dalstra, M., Huiskes, R., van Erning, L. 1995. Development and validation of a three-dimensional finite element model of the pelvic bone, Journal of biomechanical engineering 117 (1995), 272–8.

[10] Anderson, A. E., Peters, C. L., Tuttle, B. D., Weiss, J. A. 2005. Subject-specific finite element model of the pelvis: development, validation and sensitivity studies. Journal of biomechanical engineering 127 (2005), 364–73.

[11] Phillips, A. T., Pankaj, P., Howie, C. R., Usmani, A. S., Simpson, A. H. 2007. Finite element modelling of the pelvis: inclusion of muscular and ligamentous boundary conditions. Medical Engineering & Physics 29 (2007), 739–48.

[12] García, J. M., Doblaré, M., Seral, B., Seral, F., Palanca, D., Gracia, L. 2000. Three-dimensional finite element analysis of several internal and external pelvis fixations. Journal of biomechanical engineering 122 (2000), 516–22.

[13] Majumder, S., Roychowdhury, A., Pal, S. 2007. Simulation of hip fracture in sideways fall using a 3D finite element model of pelvis-femur-soft tissue complex with simplified representation of whole body. Medical Engineering & Physics 29, 10 (2007), 1167–1178.

[14] Li, Z., Kim, J. E., Davidson, J. S., Etheridge, B. S., Alonso, J. E., Eberhardt, A. W. 2007. Biomechanical response of the pubic symphysis in lateral pelvic impacts: a finite element study. Journal of biomechanic 40, 12 (2007), 2758–66.

[15] McLauchlan, G. J., Gardne, D. L. 2002. Sacral and iliac articular cartilage thickness and cellularity: relationship to subchondral bone end-plate thickness and cancellous bone density. Rheumatology 41 (2002), 375–80.

[16] Liao, S.-H., Tong, R.-F., Dong, J.-X. 2007. Anisotropic finite element modeling for patient specific mandible. Computer Methods and Programs in Biomedicine 88, 3 (2007), 197–209.

[17] Ebraheim, N. A., Xu, R., Biyani, A., Nadaud, M. C. 1997. Morphologic considerations of the first sacral pedicle for iliosacral screw placement. Spine 22, 8 (1997), 841–6.

[18] Comstock, C. P., van der Meulen, M. C., Goodman, S. B. 1996. Biomechanical comparison of posterior internal fixation techniques for unstable pelvic fractures. Journal of orthopaedic trauma 10, 8 (1996), 517–22.

[19] Yinger, K., Scalise, J., Olson, S. A., Bay, B. K., Finkemeier, C.G. 2003. Biomechanical comparison of posterior pelvic ring fixation. Journal of orthopaedic trauma 17 (2003), 481–7.

[20] Taddei, F., Cristofolini, L., Martelli, S., Gill, H. S., Viceconti, M. 2006. Subject-specific finite element models of long bones: an in vitro evaluation of the overall accuracy. Journal of Biomechanics 39 (2006), 2457–67.