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Biomechanical analysis of the fixation systems for anterior column and posterior hemi-transverse acetabular fractures



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ABSTRACT

Objective: The aim of this study was to evaluate the biomechanical properties of common fixation systems for complex acetabular fractures.

Methods: A finite element (FE) pelvic model with anterior column and posterior hemi-transverse acetabular fractures was created. Three common fixation systems were used to fix the posterior wall acetabular fractures: 1. Anterior column plate combined with posterior column screws (group I), 2. Anterior column plate combined with quadrilateral area screws (group II) and 3. Double-column plates (group III). And 600 N, representing the body weight, was loaded on the upper surface of the sacrum to simulate the double-limb stance. The amounts of total and relative displacements were compared between the groups.

Results: The total amount of displacement was 2.76 mm in group II, 2.81 mm in group III, and 2.83 mm in group I. The amount of relative displacement was 0.0078 mm in group II, 0.0093 mm in group III and 0.014 mm in group I.

Conclusion: Our results suggested that all fixation systems enhance biomechanical stability significantly. Anterior column plate combined with quadrilateral area screws has quite comparable results to double column plates, they were superior to anterior column plate combined with posterior screws.

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Acetabular fractures are a relatively common type of fracture. Among these fractures, simple fractures account for a very small proportion.¹ Approximately 35% of acetabular fractures involve the posterior wall. This pattern is the most common, and roughly 76% of these injuries are accompanied by additional fractures.² Few studies have considered complex pelvic fractures separately or determined functional outcomes using validated instruments.^{2–4} Specifically, the anterior column and posterior hemi-transverse acetabular fractures account to about 5% of all pelvic fractures and are very difficult to manage.⁵

Acetabular fractures are commonly treated through open reduction and internal fixation, especially if the incongruity exceeds 3 mm and/or the hip joint is unstable.⁶ An extended or combined approach that involves column plates and lag screws has

been utilized for complex pelvic fractures. Sawaguchi et al used anterior column lag screw fixation combined with posterior column plate to fix the transverse acetabular fracture, and found that this method could provide a degree of stability indifferent from that of other methods, and with minimal exposure and devascularization of the pelvis.⁷ Wolf et al used two column plates to treat the complex fractures and concluded that this modification could provide a helpful and easy alternative to the more demanding original exposure.⁸ Yildirim et al⁹ tested the five different fixation alternatives of stabilization of transverse acetabular fractures under two basic physiological loading conditions: standing and sitting utilizing a finite element (FE) model. The authors found that the posterior column plating combined with an anterior column screw has quite comparable results to a double column plating in transverse fractures, suggesting that the two column fixations might be unnecessary. Thus, the anterior column plate combined with posterior column screws (P&PS) and the double column plates (P*2) are commonly used to treat the anterior column and posterior hemi-transverse acetabular fractures. Except for a few simple ones,

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almost all acetabular fractures involve the quadrilateral area.¹⁰ Placing quadrilateral area lag screws via an anterior approach was a novel method to cure complex acetabular fractures, which could generate a certain clinical result and had obtained a China state patent.¹¹ To enhance the stability of fracture fixations, researchers in orthopedic trauma management generally apply anterior column plate combined with quadrilateral area screws (P&QS).¹¹

In this study, our aim was to evaluate the biomechanics of three fixation systems for the anterior column and posterior hemi-transverse acetabular fractures through FE analysis. The biomechanics of these fixation systems are assessed based on the effective stiffness levels, stress distributions, force transfer and displacements difference along their fracture lines.

Materials and methods

FE model of the pelvis

The model of a 40-year-old, 175 cm tall subject weighing 65 kg was created through laser topography using a 16-slice spiral CT with an accuracy of 0.5 mm. The accurate geometric model of the pelvis was established according to the bony contour that can be distinguished in the CT gray scale in Mimics software.^{6,12} The point cloud was converted to the surface of the pelvis. Bony tissues were meshed using a combined artificial and automatic division method using the ANSYS-ICEM and Hypermesh software. Cortical bones were meshed into eight nodes with non-linear solid hexahedron elements (C3D8), which were offset from the cancellous bone in Hypermesh. The soft tissues (i.e. end-plates, cartilage and pubic symphysis) between the pelvic bones were meshed into hexahedron elements in Hypermesh (Fig. 1). In order to ensure the convergence of optimization and the consistence of displacement between adjacent tissues, the shared nodes contact was used between tissues in the Hypermesh software. Tied contacts were used between tissues with surfaces that were adjacent to each other in the Abaqus 12.0 software to ensure that no relative displacement occurs. Mesh sensitivity studies revealed that further refinement does not improve calculation accuracy significantly. Table 1 presents the properties of the pelvic bone.

The pelvic ligaments were modeled as truss elements (element length was 2 mm), which permitted only axial tensile force transmission. The pelvic ligaments included all the major ligaments: the sacroiliac ligament ring, sacrospinous, sacrotuberous,

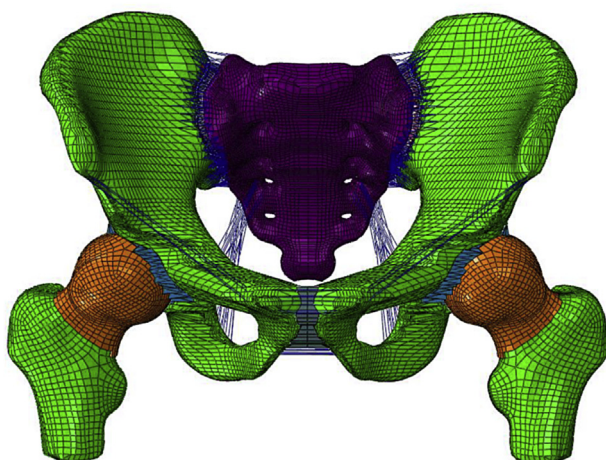


Fig. 1. Finite element model of the pelvis.

Table 1
Material properties of the pelvic bone.^{2,8}

Tissue	Elasticity modulus (MPa)	Poisson ratio (ν)	Thickness (mm)
Cortical bone	17000	0.3	
Cancellous bone	150	0.2	
End plate (sacrum)	24	0.4	0.23
Cartilage (sacrum)	54	0.4	3.00
Cartilage (ilium)	24	0.4	1.00
End plate (ilium)	54	0.4	0.36
Pubic symphysis	5	0.495	

inguinal, superior pubic, and arcuate pubic. Table 2 depicts the properties of these ligaments.

Fragment lines

The anterior column and posterior hemi-transverse acetabular fractures was determined by two converging lines. The former originates from the anterior superior spine and the latter from the ischial spine or just above this part (Fig. 2).¹⁰ Additionally, the elasticity modulus of the elements along the fracture line weakens to one tenth of normal cancellous bone.

Surgical techniques

Anterior column and posterior hemi-transverse acetabular fractures can be effectively treated through open reduction and internal fixation that use column plates and lag screws.¹³ The fixation device was composed of Nitinol (NiTi), a shape-memory alloy due to its inherent advantages, including: the shape-memory effect, remarkable resistance to wear and corrosion and good histocompatibility.¹⁴

In the anterior column plate combined with posterior column screws (P&PS) technique, the anterior column plate was implemented from the inner surface of the ilium to the superior surface of the superior pubic ramus. The screw was incorporated from the outer surface of the quadrilateral area superior to the arcuate line and into the ischial spine. The column plate was bent to meet the surgical requirement. The interface between the plates and the bone was modeled as face-to-face contact with a frictional coefficient of 0.1 to simulate the slide between the joint surfaces.^{15,16} The embedded contact type was used to restrict the slide between the interfaces of the screws and the bones.¹⁷ The screws were simulated as rod-like structures, which had a diameter of 3.5 mm.

In the anterior column plate combined with quadrilateral area screws (P&QS) technique, the position at which the column plate attached was almost similar to that in the former system. The screws in the quadrilateral area were inserted into the outer surface along the arcuate line and into the ischial spine. Two quadrilateral area screws were fixed by the column plate and cortical bone.

Table 2
Material properties of the pelvic ligaments.^{2,8}

Tissue	Elasticity modulus (MPa)	Poisson ratio (ν)
Sacroiliac ligament ring	350	0.495
Sacrospinous	29	0.495
Sacrotuberous	33	0.495
Inguinal	2.6	0.495
Superior pubic	19	0.495
Arcuate pubic	20	0.495

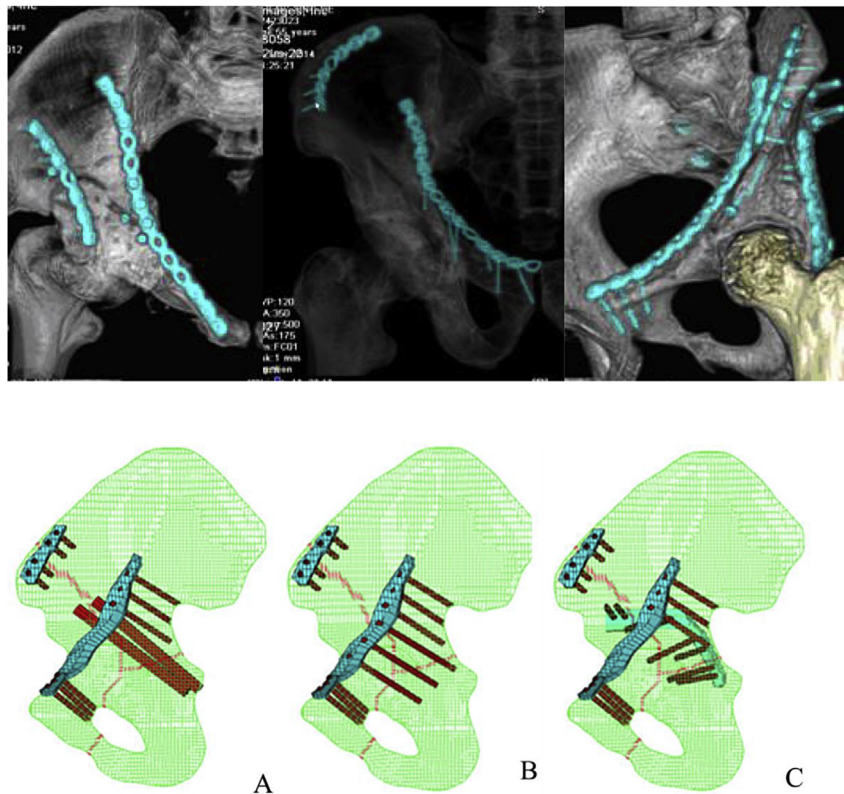


Fig. 2. Finite element models of the (A) P&PS, (B) P&QS, and (C) P*2 fixation systems. P&PS: anterior column plate combined with posterior column screws. P&QS: anterior column plate combined with quadrilateral area screws. P*2: double column plates.

In the double column plates (P*2) technique, if the fragment gap in both the anterior and posterior parts of the acetabulum is wide, the anterior and posterior plates should be combined.¹⁸ The anterior column plate was similar to that of former systems. Moreover, the posterior column plate was applied to the outer surface of the ilium. The acetabular rim was then incorporated into the ilium body above the acetabular dome. Attention was paid to prevent the screws from intersecting with one another during insertion.

To secure the clinical effectiveness of internal fixation in all fixation systems, a small plate was implanted at the end of the anterior superior spine.

The double limb stance was exerted on each model. The model was placed in a specific neutral position that was defined with the iliac wings level (coplanar in the horizontal plane).⁷ In the sagittal plane, the proximal femoral shaft was vertical. The degrees of freedom at the end of the femur were restrained to represent the double limb stance. A force of 600 N, representing the body weight, was loaded on the upper surface of the sacrum.¹⁷

Results

Fig. 3 shows both the distribution of the von Mises stress and displacement in the iliac bone of the normal model. The highest displacement in the iliac bone was 2.86 mm, a value similar to those in previous studies.¹¹ The regions of stress concentration were observed at the superior rim of the acetabulum and on the ilium superior to the acetabulum, which is consistent to previous models.^{19,20} These findings show that the FE model could be used to evaluate the biomechanical property of the pelvis.

Table 3 presents the effective stiffness levels of the normal model, fracture model, and three fixation systems. The effective

stiffness levels under the fixation systems were slightly higher than those obtained under fracture configurations. The fixation methods did not vary significantly; however, the second fixation system (P&QS) served the lowest displacement (2.76 mm), followed by the third fixation system (P*2) (2.81 mm) and then the first fixation system (P&PS) (2.83 mm). In addition, the effective stiffness values were similar to those obtained from *in vitro* experiment.¹¹

Fig. 4 displays the von Mises stress under five different configurations. Once fractured, the stress distribution on the iliac bone changed and the fracture line with a small elastic modulus experienced little stress. In the fracture model, the stress distributed in most parts of the iliac bone was lower than that of the other four models. The stress distributions in the iliac bone differed as well, especially with respect to the positions of the implanted screws and of those attached to the edge of the column plates. Specifically, in the third fixation system, the position at which the plates were attached also experiences larger stress compared to other systems.

Fig. 5 shows the von Mises stress distribution that corresponds to each fixation system in a standing stance. The stress is distributed unevenly on the lag screws. Stress was heightened in the middle of the two lag screws in the first fixation system (P&PS), and the higher stress in the column plates was noted in the regions where the screws were tightened. The stress in P&QS was maximized in the middle of the lag screws, which bind the fracture lines. These screws experience the highest stress compared with other screws. In addition, the screws fixed by the column plate were less stressed than the lag screws. On the other hand, the stress distribution in the third fixation system (P*2) was almost similar to those in the former two fixation systems, whereas the posterior column plate was considerably stressed. As per the stress distribution pattern in the column plate, the areas connected to the fracture line

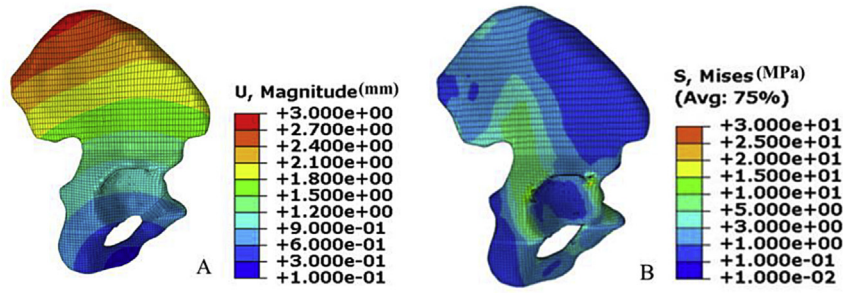


Fig. 3. Distributions of (A) stress and (B) displacement in the iliac bone.

Table 3
Effective stiffness levels of the fixation systems.

	Displacement (mm)	Effective stiffness level (N/mm)
Normal model	2.86	209
Fracture model	2.99	201
P&PS	2.83	212
P&QS	2.76	216
P*2	2.81	214

P&PS: anterior column plate combined with posterior column screws.
P&QS: anterior column plate combined with quadrilateral area screws.
P*2: double column plates.

were highly stressed as well. Hence, the column plate was installed to maintain the original position of the fracture component and to generate an artificial surface for the intact bone.

To evaluate the mechanism of the fixation systems, two paths were generated along the fracture line. One path ran along the posterior iliac fragment that was connected to the sacroiliac joint (Fig. 6A). The other followed the anterior column fragment and was put in contact with the pubic symphysis (Fig. 6B). Fig. 6C and D depicts the displacements along the paths of different models.

Compared to the normal model, the overall motion at the anterior column was minimum when P&QS was performed (0.0078 mm). The second-best fixation was with the P*2 system (0.0093 mm). Fixation with P&PS served a larger difference (0.014 mm) compared to the other fixation systems, while the value was far lower than the relative difference compared to the fracture model (0.22 mm).

Discussion

This study evaluates the biomechanics of the treatment of the anterior column and the posterior hemi-transverse acetabular fractures through FE analysis. Three different fixation systems (P&PS, P&QS and P*2) were developed based on extensive clinical experience and have been recommended in stabilization of the fractures. The mechanisms of the three fixation systems were evaluated in terms of effective stiffness levels, stress distributions, force transfers and displacements along fracture lines.

Complex acetabular fractures are generally treated by an open anatomic reduction of the articular surface in combination with rigid internal fixation.²¹ Maintaining the stability of the pelvic bone is crucial and depends on the blocking effect of the acetabular

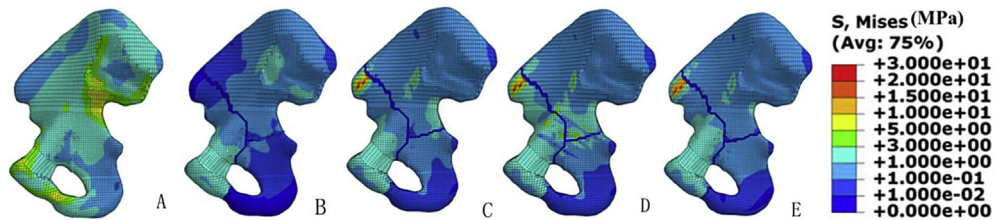


Fig. 4. Stress distribution under different conditions. (A) Stress distribution in the intact model. (B) Stress distribution in the fracture model. (C) Stress distribution in P&PS. (D) Stress distribution in P&QS. (E) Stress distribution in P*2. P&PS: anterior column plate combined with posterior column screws. P&QS: anterior column plate combined with quadrilateral area screws. P*2: double column plates.

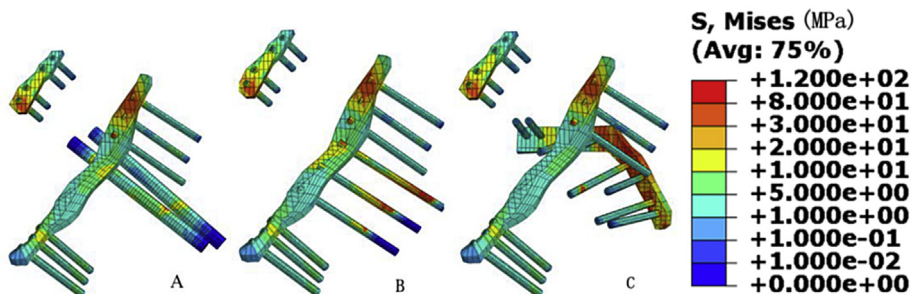


Fig. 5. (A) Stress distribution in P&PS. (B) Stress distribution in P&QS. (C) Stress distribution in P*2. P&PS: anterior column plate combined with posterior column screws. P&QS: anterior column plate combined with quadrilateral area screws. P*2: double column plates.

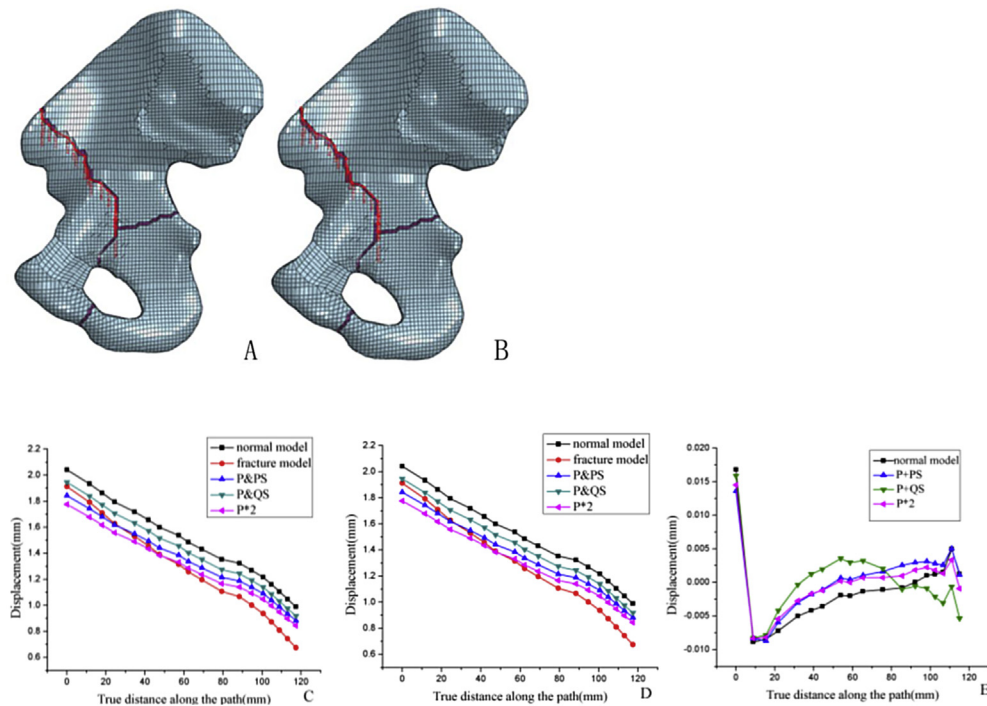


Fig. 6. Displacement along two paths. (A) Path along the posterior iliac fragment. (B) Path along the anterior column fragment. (C) Displacement along the first path. (D) Displacement along the second path. (E) Difference in displacement between the two paths.

bone.²² A fixation with a reconstruction plate that extends from the inner surface of the ilium to the superior surface of the superior pubic ramus is considered ideal for most complex pelvic fractures, given the anatomical and biomechanical characteristics of the acetabulum. However, the fixation system with column plate alone cannot produce acceptable clinical and radiological outcomes. Hence, posterior column screws, quadrilateral area screws or another plate were incorporated into the system to reduce the risk of system failure.^{7,11,18,23}

The acetabulum represents a basin-like anatomic structure that bears the body weight and the resultant force from the ground, and accommodates ambulatory activity and hip joint mobility.²⁴ Except for a few simple fractures, almost all acetabular fractures involve the quadrilateral area. The current treatment basically only involves no fixation or indirect fixation to the fracture line to avoid the risk area. When the screws were away from the acetabular fracture, the reliable degree of fixation decreased by approximately 50%, and the stability of the acetabulum decreased.^{25,26} So the reduction and stability of the quadrilateral area in the operation should be emphasized and not neglected.

The screws that attach the fracture line are more stressed than those in other positions. This finding may be ascribed to either the difference in the relative displacements of the split parts or to the difference of the materials used. Furthermore, the stress levels in the screws could correspond to their functions; thus, the lag screws are more stressed than the screws fixing the column plates. Higher stress value could be observed near the fracture line in the column plates; therefore, the lag screws fit closely to the irregular surfaces to overcome the resistance generated by shear and torsion, and column plates with lag screws effectively buttresses the fracture fragments to enhance the pelvic stability.¹⁵

For the relative displacement along the fracture paths, the second fixation system (P&QS) served minimum difference compared to normal model, the third (P*2) and first (P&PS) fixation systems followed. These results were similar to those obtained from another experiment and FE model.⁹ Yildirim et al found that column plating

combined screws provided comparable results to a double column plating in transverse fractures, suggesting that two column fixations might be unnecessary.⁹

Our study was based on FE analysis; thus, the following points should be noted. First, the comparison results were dependent on the accuracy of the FE model. The quality of the pelvic model was significantly affected by the difficulty of simulating the nonlinear characteristics of the ligaments, muscles, skin and fat. Second, the effect of the fixation systems in biomechanical study was determined by several factors, such as operative time, infection, increased blood loss, abductor weakness, and heterotopic ossification.¹¹ Furthermore, specific problems associated with internal fixation may be induced such as the intraarticular penetration of screws or the failure of fixation systems. Moreover, the long-term effect on the functional outcome and cost of fixation systems remains unassessed through FE analysis. Therefore, further basic research on the assessment of pelvic injury should be conducted to reach a more precise deduction.

In conclusion, all three different fixation systems (P&PS, P&QS, and P*2) are powerful in increasing the approximate biomechanical stability. Anterior column plate combined with quadrilateral area screws has quite comparable results to double column plates and is superior to anterior column plate combined with posterior screws.

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References

1. Moed BR, WillsonCarr SE, Watson JT. Results of operative treatment of fractures of the posterior wall of the acetabulum. *J Bone Jt Surg.* 2002;84(5):752–758.

2. Matta JM. Operative treatment of acetabular fractures through the ilioinguinal approach – a 10-year perspective. *Clin Orthop Relat Res.* 1994;305:10–19.
3. Lin HH, Hung SH, Su YP, Chiu FY, Liu CL. Cerclage wiring in displaced associated anterior column and posterior hemi-transverse acetabular fractures. *Injury.* 2012;43(6):917–920.
4. Cole JD, Bolhofner BR. Acetabular fracture fixation via a modified stoppa limited intrapelvic approach description of operative technique and preliminary treatment results. *Clin Orthop Relat Res.* 1994;305:112–123.
5. Martinez CR, Di Pasquale TG, Helfet DL, Graham AW, Sanders RW, Ray LD. Evaluation of acetabular fractures with two-and three-dimensional CT. *Radiographics.* 1992;12(2):227–242.
6. Anderson AE, Peters CL, Tuttle BD, Weiss JA. Development and validation of a subject-specific finite element model of the pelvis: assessment of model sensitivity. In: *Proceedings of Computer Methods in Biomechanics and Biomedical Engineering.* Madrid: FIRST Numerics; 2004. ISBN 0-9549670-0-3.
7. Sawaguchi T, Brown TD, Rubash HE, Mears DC. Stability of acetabular fractures after internal fixation: a cadaveric study. *Acta Orthop.* 1984;55(6):601–605.
8. Wolf H, Wieland T, Pajenda G, Vecsei V, Mousavi M. Minimally invasive ilioinguinal approach to the acetabulum. *Injury.* 2007;38(10):1170–1176.
9. Yildirim AO, Alemdaroglu KB, Yuksel HY, Öken ÖF, Ucaner A. Finite element analysis of the stability of transverse acetabular fractures in standing and sitting positions by different fixation options. *Injury.* 2015;46:S29–S35.
10. Pierannunzi L, Fischer F, Tagliabue L, Calori GM, D'Imporzano M. Acetabular both-column fractures: essentials of operative management. *Injury.* 2010;41(11):1145–1149.
11. Wu Y, Cai X, Liu X, Zhang H. Biomechanical analysis of the acetabular buttress-plate: are complex acetabular fractures in the quadrilateral area stable after treatment with anterior construct plate-1/3 tube buttress plate fixation? *Clinics.* 2013;68(7):1028–1033.
12. Dalstra M, Huiskes R. Load transfer across the pelvic bone. *J Biomech.* 1995;28(6):715–724.
13. Gettys FK, Russell GV, Karunakar MA. Open treatment of pelvic and acetabular fractures. *Orthop Clin N Am.* 2011;42(1):69–83.
14. Zhang Y, Zhao X, Tang Y, Zhang C, Xu S, Xie Y. Comparative study of comminuted posterior acetabular wall fracture treated with the Acetabular Tridimensional Memory Fixation System. *Injury.* 2014;45(4):725–731.
15. Brolin K, Halldin P. Development of a finite element model of the upper cervical spine and a parameter study of ligament characteristics. *Spine (Phila Pa 1976).* 2004;29(4):376–385.
16. Zhang QH, Teo EC, Ng HW, Lee VS. Finite element analysis of moment-rotation relationships for human cervical spine. *J Biomech.* 2006;39(1):189–193.
17. Olson SA, Bay BK, Pollak AN, Sharkey NA, Lee T. The effect of variable size posterior wall acetabular fractures on contact characteristics of the hip joint. *J Orthop Trauma.* 1996;10(6):395–402.
18. Andersen RC, O'Toole RV, Nascone JW, Sciadini MF, Frisch HM, Turen CW. Modified stoppa approach for acetabular fractures with anterior and posterior column displacement: quantification of radiographic reduction and analysis of interobserver variability. *J Orthop Trauma.* 2010;24(5):271–278.
19. Phillips A, Pankaj P, Howie CR, Usmani AS, Simpson A. Finite element modelling of the pelvis: inclusion of muscular and ligamentous boundary conditions. *Med Eng Phys.* 2007;29(7):739–748.
20. Dalstra M, van Erning L, Huiskes R. Development and validation of a three-dimensional finite element model of the pelvic bone. *J Biomech Eng.* 1995;117(3):272–278.
21. Briffa N, Pearce R, Hill AM, Bircher M. Outcomes of acetabular fracture fixation with ten years' follow-up. *J Bone Jt Surg Br Vol.* 2011;93(2):229–236.
22. Gilliland JM, Anderson LA, Henninger HB, Kubiak EN, Peters CL. Biomechanical analysis of acetabular revision constructs: is pelvic discontinuity best treated with bicolumnar or traditional unicolumnar fixation? *J Arthroplast.* 2013;28(1):178–186.
23. Schopfer A, DiAngelo D, Hearn T, Powell J, Tile M. Biomechanical comparison of methods of fixation of isolated osteotomies of the posterior acetabular column. *Int Orthop.* 1994;18(2):96–101.
24. Kubota M, Uchida K, Kokubo Y, et al. Changes in gait pattern and hip muscle strength after open reduction and internal fixation of acetabular fracture. *Arch Phys Med Rehabil.* 2012;93(11):2015–2021.
25. Wu T, Chen W, Zhang Q, et al. Biomechanical comparison of two kinds of internal fixation in a type C zone II pelvic fracture model. *Chin Med J Engl.* 2015;128(17):2312–2317.
26. Harnroongroj T, Asavamongkolkul A, Chareancholvanich K. Reconstruction of the pelvic brim and its role in the reduction accuracy of displaced T-shaped acetabular fracture. *J Med Assoc Thai.* 2000;83(5):483–493.