A Novel Anatomical Locking Plate Fixation for T-Shaped Acetabular Fracture: Finite Element Analysis

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Abstract

Purposes: To compare the biomechanical stability of the plate and eight different kinds of internal fixation for T-shaped acetabular fracture using finite element analysis.

Methods: Finite element models of T-shaped acetabular fractures were created in this study based on CT data from fourth-generation synthetic sawbones. Nine different fixation models, including the novel anatomical locking plate and eight other internal fixations were established. The biomechanical tests were compared. We recorded and analyzed the anterior, posterior and inferior displacements of nine finite element models after applying the same load.

Results: The anterior displacement, posterior displacement and inferior displacement fixed by the novel anatomical locking plate were 0.2805 mm, 0.3177 mm and 0.6842 mm, respectively. The smallest and largest anterior displacements of the nine models were found with 7.3 mm anterior lag screws plus a posterior locking plate and 5.5 mm anterior lag screws plus a posterior reconstruction plate, respectively. The smallest and largest posterior displacements of the nine models were found with the novel anatomical locking plate and 5.5 mm anterior lag screws plus a posterior reconstruction plate, respectively. The smallest and largest inferior displacements of the nine models were found with the novel anatomical locking plate and 5.5 mm anterior lag screws plus a posterior reconstruction plate, respectively. Regarding the fixations by the same reconstruction or locking plate, the magnitude of displacement increased as the diameter of the lag screw decreased. With the same diameter screws, the whole displacements of the models fixed by locking plates were smaller than those fixed by reconstruction plates.

Conclusion: The stability of the novel anatomy locking plate provides sufficient stabilization and resembles other fixation instructions for the fixation of T-shaped acetabular fractures.

Keywords: Acetabular fracture; Finite element analyze; Anatomy locking plate; Anterior column lag screw

Introduction

Acetabular fractures are infrequent, with an incidence of 3 per 100,000 annually [1]. The majority of the fractures are the result of high-energy injuries caused by traffic accidents or accidental falls [2-4]. With the increase in the aging population, the incidence of elderly acetabular fracture caused by low-energy injuries continues to increase [5]. These fractures in elderly patients become a challenging problem due to their more complex fracture patterns, poor bone quality and underlying comorbidities [6-8]. The one-year mortality rates are as high as 38% [9]. To improve prognosis after acetabular fracture, conservative treatment has been replaced by open reduction and internal fixation [10-12]. The purpose of surgery is to achieve anatomical reduction and congruency with the femoral head [13,14]. Fractures involving the posterior column of the acetabulum are common and often treated with a combination of reconstruction plates and screws. However, due to the anatomical complexity and morphological variability of the surface of the acetabular posterior column, it is difficult to anatomically contour the reconstruction plate sufficiently [15]. Pre-contouring the plate during surgery repeatedly is often inevitable, which may decrease the strength of fixation. Moreover, the inadequate pre-contouring of the plate may lead to fracture redisplacement well after restoration. This surgical procedure has been carried out for nearly half a century, but its optimal performance is still challenging for the majority of surgeons [16,17]. Currently, locking plates are also used in acetabular fracture fixation [18]. Although the locking plate fixes the acetabular fracture

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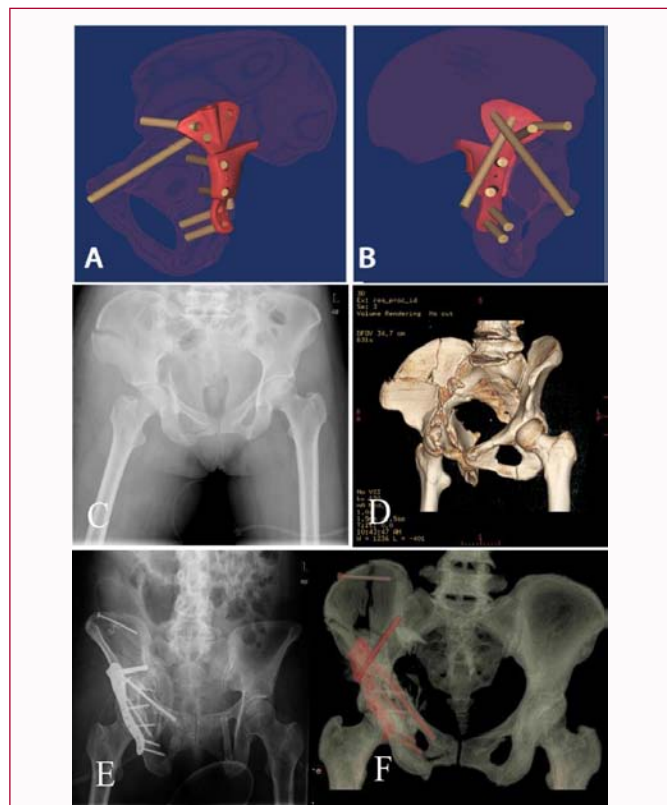
Figure 1: The novel anatomical locking plate and the patient from the clinic.

Figure 2: The displacements of the T-shaped acetabular fracture fixation using the nine methods.

Figure 3: The displacement contours of the nine different internal fixations. (a) NALP; (b) ARPPRP; (c) ALPPLP; (d) ASPRP5.5; (e) ASPRP6.5; (f) ASPRP7.3; (g) ASPLP5.5; (h) ASPLP6.5; (i) ASPLP7.3.

without sufficient pre-bending, there is the risk of screw penetration into the hip, and the locking holes cannot be used after curving the locking plate moderately. Therefore, it is necessary to design a new anatomical locking plate that matches the surface anatomical morphology of the posterior column without pre-bending during surgery and to reduce the difficulty of the operation when fixing the acetabular fracture clinically.

In our previous study, we established a mean surface morphology of the Chinese acetabular posterior column by point cloud data accessed from 171 three-dimensional models of the acetabulum of normal Chinese people scanned by computer tomography [19]. With this mean surface morphology, we successfully designed a novel anatomical locking plate without pre-contouring during surgery because its shape can be matched with the surface morphology of the posterior column of the acetabulum. This anatomical plate combines the advantage of a locking plate with preset locking holes to prevent screws penetrating into the hip. In addition, this anatomical locking plate also provides guide holes for placing anterior column lag screws and magic screws (Figure 1). Theoretically, we can restore the inverted Y-shaped structure of the acetabulum excellently by fixing the anterior column and posterior column and reduce the risk of fracture fixation failure simultaneously through a single posterior approach.

The purpose of this article was to verify the biomechanical stability of this new plate fixation for T-shaped acetabular fractures using finite element analysis to provide an effective theoretical basis for clinical use.

Materials and Methods

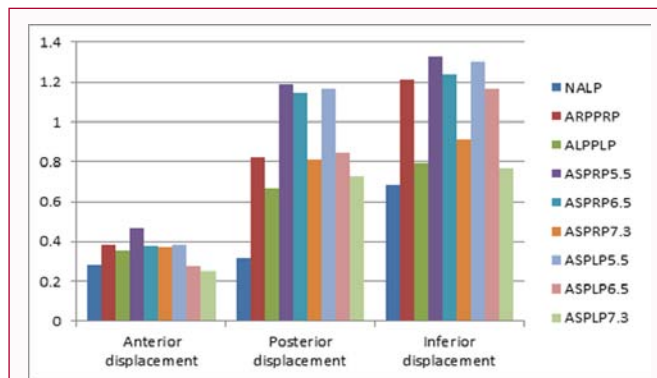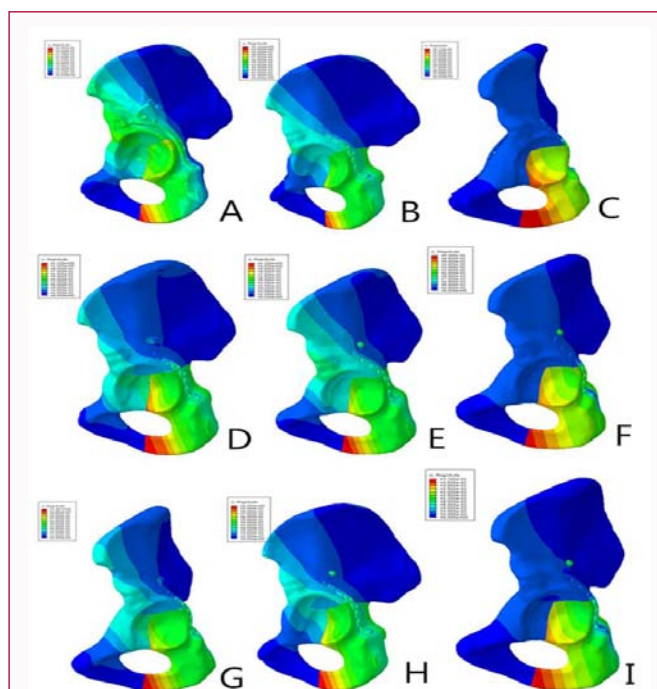Fourth generation synthetic semi-pelvic sawbones (MODEL3405#,

Pacific Research Laboratories, Vashon, WA) were scanned by computed tomography (CT, GE Medical Systems/light speed 16) to obtain 227 pictures in Digital Imaging and Communications in Medicine (DICOM) format. To reconstruct the three-dimensional model of the acetabulum, the images in DICOM form were imported into image processing software (Mimics, Materialise's Inter-active Medical Image Control System, Materialize, Belgian). According to the article written by Letournel E [20], a T-shaped acetabular fracture is defined as a transverse fracture combined with an additional fracture line that divides the ischiopubic into two parts. We simulated the T-shaped fracture by imitating the transverse fracture line located lateral to the iliopectineal eminence from the anterior wall to the posterior column and exited at the greater sciatic notch. The inferior fracture traversed the midportion of the quadrilateral surface to the obturator foramen and divided the ramus into two equal parts [21].

The three-dimensional models of the novel anatomical locking plate and relevant 5.5-mm anterior column lag screw were provided

by Weigao Orthopedic Device Co. (Weihai, Shandong, China). The reconstruction plates, locking plates, screws and anterior column lag screws used in this study were produced by Depuy Synthes (West Chester, USA). The anterior column reconstruction plates and locking plates were 3.5 mm thick with 10 holes, and the posterior column reconstruction plates and locking plates were 3.5 mm thick with 8 holes. The screws were 4 mm in diameter. There were three diameters of anterior column lag screws used in this study: 7.3 mm, 6.5 mm and 5.5 mm. All three-dimensional models of internal fixation devices were three-dimensionally scanned and saved in STP format.

The element type of the T-shaped acetabular fracture model was set as a 4-node tetrahedron, and the novel anatomical locking plate and other internal fixation devices were set as 10-node quadratic tetrahedrons in this FE model. Young's modulus and Poisson's ratio were set at 16 GPa and 0.265 for cortical bone, 0.155 GPa and 0.2 for cancellous bone, 110 GPa and 0.3 for all plates and screws, respectively. The details of each part are shown in table 1.

The boundary condition that constrained six degrees of freedom of the pubic symphysis and the sacroiliac joint surface was employed, and frictional contact was used between the fracture fragments. We conducted the load to be oriented 45 degrees superomedially on the coronal plane and 25 degrees posteriorly on the sagittal plane with 600N to simulate incomplete weight-bearing after surgery for acetabular fracture [22]. The anterior displacement, posterior displacement and inferior displacement were recorded and analyzed.

Then, we established nine fixation models of T-shaped acetabular fracture: (1) Novel Anatomical Locking Plate (NALP), (2) Anterior Column Reconstruction Plate Plus Posterior Column Reconstruction Plate (ARPPRP), (3) Anterior Column Locking Plate Plus Posterior Column Locking Plate (ALPPLP), (4) 5.5-mm Anterior Column Lag Screw Plus Posterior Column Reconstruction Plate (ASPRP5.5), (5) 6.5-mm Anterior Column Lag Screw Plus Posterior Column Reconstruction Plate (ASPRP6.5), (6) 7.3-mm Anterior Column Lag Screw Plus Posterior Column Reconstruction Plate (ASPRP7.3), (7) 5.5-mm Anterior Column Lag Screw Plus Posterior Column Locking Plate (ASPLP5.5), (8) 6.5-mm Anterior Column Lag Screw Plus Posterior Column Locking Plate (ASPLP6.5), and (9) 7.3-mm Anterior Column Lag Screw Plus Posterior Column Locking Plate (ASPLP7.3).

Results

The anterior displacement, posterior displacement and inferior displacement were defined as the maximum displacement between the fragments of the anterior, posterior and inferior fracture lines in the T-shaped acetabular fracture models. The maximum anterior displacement was found in the ASPRP5.5 model at 0.4658 mm, and the minimum anterior displacement occurred in the ASPLP7.3 model at 0.2542 mm. The anterior displacement of the NALP model was 0.2805 mm and ranked third smallest, just larger than the ASPLP6.3 model, at 0.2785 mm. The minimum posterior displacement was found with the NALP fixation at 0.3177 mm, and the maximum posterior displacement was found with the ASPRP5 fixation at 1.1861 mm. The lowest inferior displacement was shown in the NALP model at 0.6842 mm, and the largest inferior displacement was shown in the ASPRP5.5 model at 1.3282 mm.

In the ASPRP7.3, ASPRP6.5 and ASPRP5.5 models fixed with a posterior column reconstruction plate, the magnitudes of anterior, posterior and inferior displacements decreased with the increasing
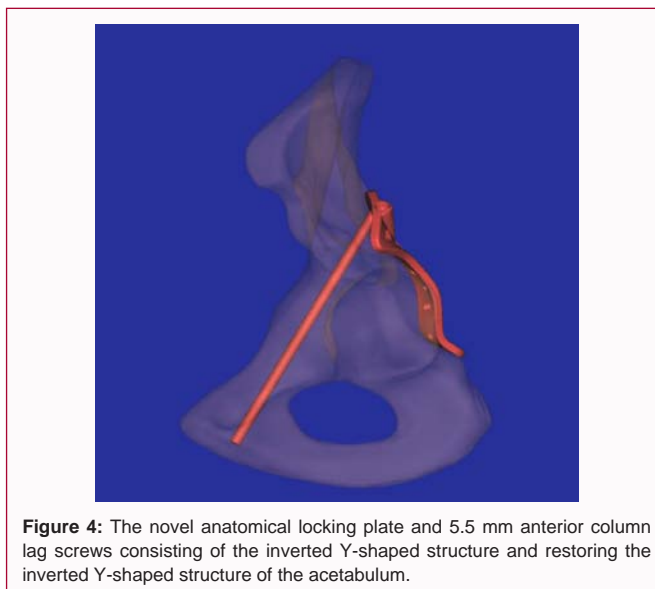
Figure 4: The novel anatomical locking plate and 5.5 mm anterior column lag screws consisting of the inverted Y-shaped structure and restoring the inverted Y-shaped structure of the acetabulum.

Table 1: Details of each part in finite element models.

	Young's modulus (GPa)	Poisson's ratio	Type of element
Cortical bone	16	0.155	C3D4
Cancellous bone	0.265	0.2	C3D4
NALP	110	0.3	C3D10
Anterior reconstruction plate	110	0.3	C3D10
Anterior locking plate	110	0.3	C3D10
posterior reconstruction plate	110	0.3	C3D10
posterior locking plate	110	0.3	C3D10
5.5mm lag screw	110	0.3	C3D10
6.5mm lag screw	110	0.3	C3D10
7.3mm lag screw	110	0.3	C3D10

Table 2: The displacements of t-shaped acetabular fracture fixation by nine methods.

	Anterior displacement	Posterior displacement	Inferior displacement
NALP	0.2805	0.3177	0.6842
ARPPRP	0.3828	0.8224	1.2129
ALPPLP	0.3562	0.6639	0.7952
ASPRP5.5	0.4658	1.1861	1.3282
ASPRP6.5	0.3795	1.1492	1.2363
ASPRP7.3	0.3692	0.8097	0.9141
ASPLP5.5	0.3845	1.1627	1.3021
ASPLP6.5	0.2785	0.8477	1.1668
ASPLP7.3	0.2542	0.7274	0.7684

diameter of the anterior column lag screws used in our study. The anterior, posterior and inferior displacements from maximum to minimum were ASPRP5.5, ASPRP6.5, and ASPRP7.3. The magnitude of displacements in the ASPLP7.3, ASPLP6.5 and ASPLP5.5 models fixed with a posterior column locking plate were similar to previous results in that the magnitude of anterior, posterior and inferior displacements decreased with increasing diameter of the anterior column lag screws.

The results showed that in the ASPLP7.3 and ASPLP7.3 models fixed with the same anterior column lag screw diameter, fixation with a posterior locking plate produced smaller displacement than fixation with a reconstruction plate. Comparing the ASPLP6.5 and ASPRP6.5 models and the ASPLP5.5 and ASPRP5.5 models, the displacements of fixations with a posterior locking plate were still smaller than the fixation with a posterior reconstruction plate. All of the displacements are shown in table 2.

The displacement contours of the nine different internal fixations showed that the fracture displacements focused on the inferior ramus of the pubis (Figure 2,3).

Discussion

The novel anatomical locking plate and 5.5-mm anterior column lag screws we designed consisted of an inverted Y-shaped structure that matched the inverted Y-shaped structure of the acetabulum [12] (Figure 4). Theoretically, there are several advantages when using this novel anatomical locking plate to fix an acetabular fracture. (1) the novel anatomical locking plate is anatomically contoured to match the surface of the posterior column of the Chinese acetabulum because its shape was designed based on the mean morphology of 171 acetabula, and as a result, surgeons could use this plate directly without precontouring by hand, which would reduce the surgical time and blood loss and possibly avoid the loss of reduction after fixation and the risk of reduction of the strength of the reconstruction plate from repeated precontouring. (2) Combined with the advantages of the locking plate, the novel anatomical locking plate we designed overcomes the lack of reconstruction plates and locking plates in clinical use. The reconstruction plates that are the most widely used for internal fixation clinically maintain the reduction of the fracture mainly through friction between the plate and the surface of bone, which may affect the blood supply to the fracture site and cause delayed union and even non-union. To enhance the strength of fixation, anatomical shapes and bicortical screw fixation are essential. However, it may waste time to precontour the reconstruction plate and may increase the risk of intra-articular penetration [23,24] that can cause traumatic arthritis. It has been reported that the incidence of traumatic arthritis in acetabular fracture surgery fixed with a traditional reconstruction plate is up to 30% [15], partly due to the damage to articular cartilage caused by intraoperative screws penetrating into the joint cavity. Unlike reconstruction plates, locking plates secure the fracture fragments mainly through the locking function between the plate and screws rather than through friction between reconstruction plate and the bone surface. The locking plate stabilizes the fracture by angular stability, which makes it possible to fix the fracture with unicortical screws and avoid screw penetration into the hip, reducing the incidence of traumatic arthritis. Moreover, the locking screws are more stable than the screws used in reconstruction plates, even in osteoporotic bone. However, this straight locking plate in clinical use still requires contouring partly by hand, which may not only lead to a lack of locking function because the locking screw thread would become deformed when bending the locking plate by hand but also lead to screw penetration into the hip because the direction of the screw holes is set in advance. The novel anatomical locking plate combines the advantages of the locking plate above with screw holes that can be directed away from important structures, reducing the incidence of traumatic arthritis. (3) The novel anatomical locking plate is equipped with minimally invasive anterior column screws and magic screws to fix acetabular

fractures. In 1998, Starr AJ et al. [25] reported minimally invasive techniques for acetabular anterior column fracture fixation using the anterior column lag screw successfully under CT guidance for the first time and achieved good clinical results. In recent years, with better understanding of the anatomy of the acetabular screw channel, minimally invasive percutaneous screw fixation for acetabular fractures are increasingly favored by clinicians, especially for obese patients and minor fracture displacement that can close the reduction. Shazar et al. [26] believed that anterior column lag screws combined with a posterior column plate for fixation of transverse acetabular fractures would be better than anterior and posterior plates together. A minimally invasive surgical approach is beneficial for reducing soft tissue damage and incision-related complications, but the surgery is difficult because it requires the surgeon to have a wealth of experience with open reduction and internal fixation and to grasp and comprehend all angles of the projected image of the acetabulum. Surgeons and patients are exposed to higher doses of radiation than traditional open reduction and internal fixation with minimally invasive surgery. Although many scholars have proposed the use of computer navigation technology to achieve percutaneous minimally invasive techniques, the difficulty of the operation and technological immaturity still restrict the promotion of this operation. The novel anatomical locking plate we designed set the guide holes to guarantee the start point for anterior column screws and magic screws to fix the anterior column and quadrilateral plate of the acetabulum, respectively, which made it easier to safely place minimally invasive screws successfully. Surgeons can fix the anterior and posterior columns simultaneously through a single Kocher-Langenbeck approach.

We conducted this study to compare the biomechanical stability of acetabular T-shaped fracture fixation using the novel anatomical locking plate and several other commonly used internal fixations with finite element analysis. In this study, the largest diameter lag screws that fit the novel anatomical locking plate were 5.5 mm due to a lack of technology. Therefore, we compared the different diameters of the anterior column lag screws, including 6.5 mm and 7.3 mm. The results showed that the minimum anterior displacement from nine internal fixations was fixation with a 7.3-mm anterior column lag screw combined with a posterior locking plate at 0.2542 mm, followed by the 6.5-mm anterior column lag screw combined with posterior column locking at 0.2785 mm. The novel anatomical locking plate ranked third smallest at 0.2805 mm and was more stable than the 5.5-mm anterior column lag screw for fixation of the acetabulum anterior column. The magnitudes of the anterior displacement in the fixation models with 5.5-mm anterior column lag screws plus a posterior reconstruction plate and 5.5-mm anterior column lag screws plus a posterior locking plate were 0.4658 mm and 0.3845 mm, respectively. We believe that the novel anatomy locking plate and anterior column lag screw constitute an inverted Y-shaped structure that unites three parts of the T-shaped acetabular fracture into a whole and restores the inverted Y-shaped structure of the acetabulum, strengthening the fixation of the anterior column. The results showed that the minimum inferior displacement and posterior displacement were both from the model fixed with a novel anatomical locking plate. As a result, we have every reason to believe that this novel anatomical locking plate fixation can provide as much stability as other fixation installations for fixation of acetabular fractures, which is worthy of use in clinical settings.

In recent years, minimally invasive acetabular screw fixation has

increased gradually. Chang JK et al. [27] used *in vitro* biomechanical experiments to show that, when fixing the anterior column and posterior column with lag screws simultaneously, the yield strength and maximum load were significantly smaller than fixation with anterior lag screws plus a posterior plate in transverse fractures. Therefore, surgeons could fix the acetabular fracture by combining minimally invasive lag screws with plates. Attias N et al. [28] reconstructed 26 three-dimensional models of the acetabulum scanned by CT and showed that the average maximum diameter of the screws that could accommodated safely in the anterior column screw channel of the acetabulum was 6.4 mm. Chen KN et al. [29] attested that 6.5 mm lag screws were generally applicable in Chinese acetabula. In our study, we compared three different diameters of anterior column lag screws, 7.3 mm, 6.5 mm and 5.5 mm, to fix T-shaped acetabular fractures, and the results showed that stability increased with increasing diameter. This result suggests that surgeons could use larger diameter lag screws to fix the anterior column of the acetabulum if possible to acquire better results. We also found that in this finite element study, when using the same diameter anterior column lag screw fixation for T-shaped acetabular fractures, the fracture displacements after loading the locking plate fixation were smaller than fixation with reconstruction plates, implying that the locking plate provide more stability than the reconstruction plate. This result is similar to the result of Mehin R et al. [30]. They found that under a load of 50N, *in vitro* biomechanical testing was not statistically significantly different when fixing the transverse acetabular fracture by locking plate only and traditional reconstruction plate plus lag screw. Tadros AM et al. [31] believed that the locking plate fixation of acetabular fractures without periosteal stripping the during operation would protect the blood supply of the fracture site and provide micromotion that was conducive to secondary fracture healing.

Unlike the traditional method for building finite element models that use normal pelvic three-dimensional models scanned by CT, we established this finite element model based on fourth generation synthetic semi-pelvic sawbones produced by Pacific Research Laboratories and proved to be effective for use in biomechanical [32-34] experiments. However, this method has some advantages. It can be compared with other finite element research models established by the same method, avoiding the differences caused by the different sample sizes and morphologies of the human pelvis. In addition, this finite element model is more convenient for comparing the results of *in vitro* biomechanical experiments using the sawbones, which is our next step.

There are limitations in this study. The hip is a complex joint with a large range of motion. Although the loading orientation in this finite element model that simulated incomplete weight-bearing after surgery for acetabular fracture was based on previous research, it is unable to simulate all movements of the hip after surgery. In addition, the novel anatomical locking plate we designed theoretically could fix acetabular fractures involving the double column simultaneously through a single posterior approach. Therefore, we should research various fractures fixed with the novel anatomical locking plate, rather than only fixing the T-shaped acetabular fracture with future research.

Conclusion

The stability of the novel anatomical locking plate we designed for fixing T-shaped acetabular fractures resembled other fixation instructions, provided sufficient stabilization and restored the inverted Y-shaped structure of the acetabulum well. We consider that if surgeons master the use of this novel anatomical locking plate, it will decrease the difficulty of acetabular surgery, decrease the duration of the operation and improve prognosis after acetabular fracture.

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