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Original Article

A novel anatomical self-locking plate fixation for both-column acetabular fractures

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ABSTRACT

Purpose: To compare the stability of the posterior anatomic self-locking plate (PASP) with two types of popular reconstruction plate fixation, i.e. double reconstruction plate (DRP) and cross reconstruction plate (CRP), and to explore the influence of sitting and turning right/left on implants.

Methods: PASP, DRP and CRP were assembled on a finite element model of both-column fractures of the left acetabulum. A load of 600 N and a torque of 8 N·m were loaded on the S1 vertebral body to detect the change of stress and displacement when sitting and turning right/left.

Results: The peak stress and displacement of the three kinds of fixation methods under all loading conditions were CRP > DRP > PASP. The peak stress and displacement of PASP are 313.5 MPa and 1.15 mm respectively when turning right; and the minimal was 234.0 Mpa and 0.619 mm when turning left.

Conclusion: PASP can provide higher stability than DRP and CRP for both-column acetabular fractures. The rational movement after posterior DRP and PASP fixation for acetabular fracture is to turn to the ipsilateral side, which can avoid implant failure.

Introduction

Both-column acetabular fractures are high-energy injuries due to fall from height, car accidents, massive object crashes, etc. It was the most severe damage to the stability of the hip joint, and multiple reconstruction plates are required for fixation. However, the failure rate of using multiple plates is high, causing traumatic arthritis and thereafter require of total hip replacement (THR). The intraoperation complications include unstable or ineffective fixation of the fracture fragments, screw invasion into the joint, etc. Postoperative complications include screw loosening, slippage or rupture, reduction loss, etc. This will lead to severe traumatic arthritis, necessitating THR.[1,2]

Double reconstruction plate (DRP) is the most popular method for posterior acetabular fixation.[3,4] When there are more than 3 comminuted fragments of the posterior wall and column of the acetabulum, 2–4 plates are often needed for fixation.[5,6] Individualized three-dimensional printing plates are not yet popular.[7] The most widely used reconstruction plate has good flexibility and is easy to be manually remodelled according to the morphological characteristics of the acetabular surface during operation. However, the disadvantages are that manual remodelling will leave scratches on the plate, and thus increasing the concentration of the internal stress in the plate as well as the risk of implant failure. In addition, intraoperative plate remodelling will delay the operation time, prolong the wound exposure time and bleeding, and increase the chance of infection. If the plate is poorly remodelled, or there is shear force between two overlapped plates, it will lead to stress shielding, implant loosening, reduction loss, raising the risk of nonunion or malunion.[1,2] Patients cannot be guaranteed early functional movements to restore hip joint function. Currently, there is a lack of effective internal fixation devices for osteoporosis patients.[8,9] Based on the abovementioned backgrounds, we designed the posterior anatomic self-locking plate (PASP) (patent number: ZL201310371875.8) on the basis of acetabular anatomy, biomechanics, and ergonomics. Even if the fracture of the posterior acetabulum is severely comminuted, the bone can be effectively fixed.

The purpose of this study is, firstly, to compare the stability of PASP with DRP and cross reconstruction plate (CRP)[10] to determine the most stable fixation implant; and secondly to explore the influence of sitting, turning right/left on these three kinds of implants, and to identify the rational postoperative movement after posterior plate fixation of acetabular fractures.

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Methods

Ethical review

Before the start of this experiment, the Ethics Committee approved the Medical College of Ningbo University affiliated Ningbo NO.6 Hospital to carry out this study (Approval No. L2018013). Patients who met the research conditions signed the medical ethics informed consent to obtain the raw imaging data of the normal pelvis. All methods were carried out in accordance with relevant guidelines and regulations. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

The pelvic sample

The author searched the data about the pelvic CT in the Radiology Department of the Medical College of Ningbo University affiliated Ningbo NO.6 Hospital from January 2018 to December 2019. Inclusion criteria were: (1) CT scan range from L_4 to lesser trochanter of femur; (2) patients aged 25–65 years; and (3) the searcher is the same person in the Radiology Department. Exclusion criteria were combination with (1) bone and/or soft tissue tumors; (2) skeletal malformation; (3) fresh pelvic or acetabular fractures; (4) old pelvic or acetabular fracture; or (5) scoliosis.

CT data of 101 normal pelvic cases (59 males and 42 females) met the inclusion and exclusion criteria and were retrieved. There was no withdrawal or missing value. According to the interquartile range principle, the values are arranged from small to large and divided into four equal parts. The pelvic CT of a 45-year-old male was selected as the sample median.

Design of the PASP

PASP includes seven functional fixation zones (Fig. 1). The screw fixation trajectory with 360° range of motion for the hip joint is designed. From a single posterior incision of the acetabulum, the hip joint was fixed in four spatial positions: superior, inferior, medial and lateral regions of the acetabular joint (Fig. 2). One PASP substitutes the fixed regions of 2–4 pieces of reconstruction plates. The special “pressure band screws, tension band screws, blocking holes”, “tension bridge and pressure bridge” were designed, which match the unique biomechanical pathway of the pressure and tension trabecular bone of the acetabulum, reasonably dispersing the compressive and tensile stresses of the hip joint, avoiding stress shielding caused by invalid or inefficient screw fixation, bearing the active loads of the hip joint as normal bone as possible, and thus helps the fracture to heal in a stable manner that is most beneficial to the patient. The locking screw on the plate effectively maintained anatomical reduction to prevent comminuted fragment re-displacement or bone loss during postoperative rehabilitation activities, and avoids the implant complications of screw loosening, slipping and breaking, etc. PASP is also suitable for osteoporosis patients (Fig. 3).

The design of positioning holes on the PASP facilitates the orientation of the upper and lower boundaries of the joint within the narrow incision space and prevents the screw from invading the joint. The positioning hole P1 is located at the superior margin of the acetabulum, and positioning hole P2/P3 at the inferior margin of the acetabulum. For larger acetabular joint, P3 was used to prevent the guide needle from invading the joint (Figs. 1, 2 and 4). The exit of each screw hole is to avoid important soft tissue structures such as superior gluteal artery and vein, superior gluteal nerve, obturator artery and vein, obturator nerve, inferior abdominal artery and vein, femoral artery and vein, femoral nerve, etc. Avoid invasion of screws into adjacent vital vessels and nerves after insertion, preventing disastrous surgical complications (Fig. 3). Considering the principle of ergonomics, the locking protective sleeve is designed to ensure the accuracy and conveniency of screw insertion, so as to prevent the screw from invading the joint or damaging the surrounding soft tissues and causing disastrous complications (Fig. 4). The vacant screw hole is used as a vascular growth channel, that is, the soft tissue growth channel, which is beneficial to the blood supply reconstruction of the fracture site.

Operative technique

Firstly, the positioning hole P2/P3 in the 7th functional fixation zone is applied to the obturator internus notch of the ischium, then a 2.0 mm diameter Kirschner wire is inserted into the screw hole or P2/P3 through the drill protection sleeve (Fig. 4). With Kirschner wire as the axis, the proximal end of the plate can slide inside and outside (Fig. 4B), so as to be in the best position to fix the fracture fragments. According to the needs of the operation, locking screws or unlocking screws can be inserted.

The 5th functional fixation zone are three “blocking holes”, which are used to stabilize the small comminuted fragments in the outer margin of the posterior wall or the avulsed small bone fragments of the glenoid labrum, preventing the bone absorption, bone loss, and the traumatic arthritis of the hip. The screws should not be inserted to prevent the screws from invading the joint (Fig. 4C/D).

Indications of PASP

PASP can be used in OTA classification types 62A1/A2, 62B1/B2/B3, 62C1/C2.[11] The details are as follows: (1) comminuted fractures of the posterior wall and posterior column of acetabulum, (2) posterior acetabulum combined with weight-bearing dome, including articular collapse compression fracture, (3) fractures of the posterior acetabulum combined with medial quadrilateral region, (4) fixation of the posterior and medial bone grafts during THR revision, and (5) osteoporosis patients, for whom PASP can stably lock the osteoporotic fragments.

Three-dimensional modelling

The scanning parameters of the CT machine (SOMATOM Definition AS128, Siemens AG): 120 kV, 250 mA, slice 0.6 mm, pitch 0.55 mm, and the scanned image were saved in DICOM format. DICOM data were imported into Mimics 12.1 software (Materialise, Leuven, Belgium) and Geomagic Studio V12.0 (Raindrop Company, USA) to establish the pelvic model (Fig. 1). The computer-aided design modelling of titanium alloy implants was completed in Solidworks software (Solidworks/UGS V2010, Dassault Systemes SA, France). The reconstruction plate parameters were 2.8 mm (thickness), 10.0 mm (width) and 3.5 mm (solid screw diameter). The average plate thickness and the screw diameter of the PASP are the same as the reconstruction plate to ensure the homogeneousness of comparison.

Finite element (FE) modelling and material properties

The ilium and sacrum are divided into the cortical and cancellous bone, and the bones are all C3D4 units (4 nodes and 4 tetrahedral unit).[12] The ligaments were used by Spring 2 units.[12–14] According to the characteristics of the anatomical structure of the pelvis, seven ligaments related to pelvic stability were established: sacroiliac ligament, sacrospinous ligament, sacrotuberous ligament, iliolumbar ligament, inguinal ligament, superior pubic ligament, and arcuate pubic ligament (Fig. 1). According to Rice's

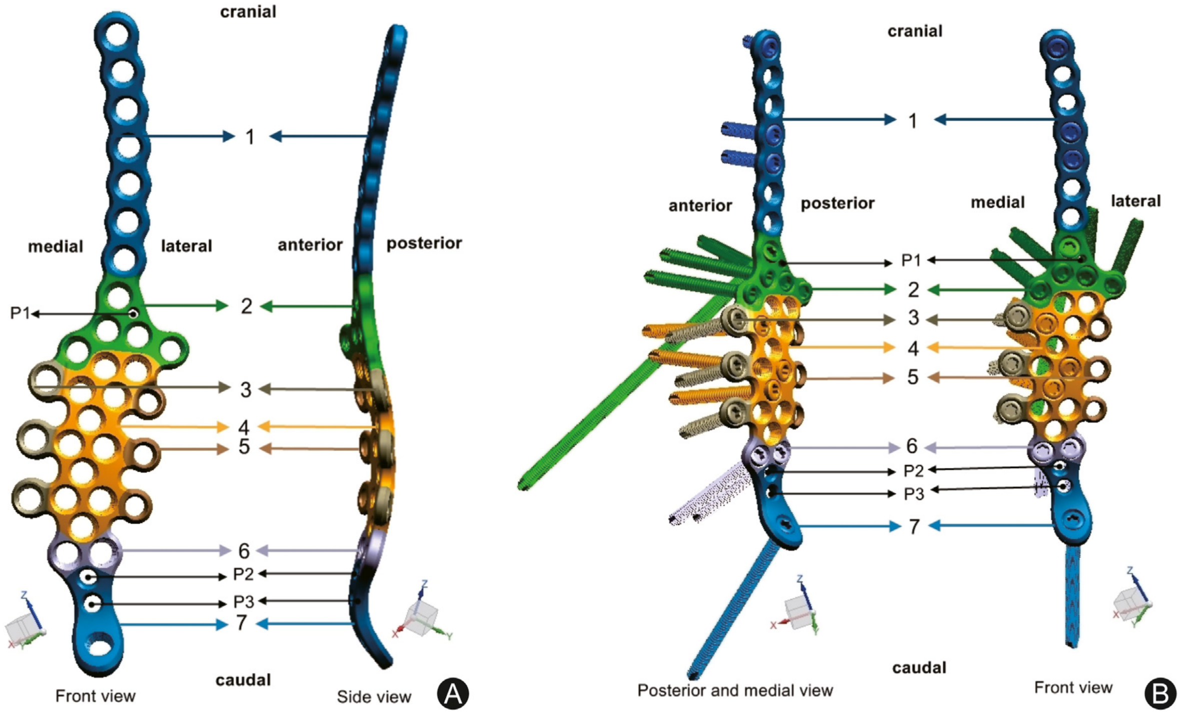

Fig. 1. Seven functional fixation zones of PASP are divided and identified by different colors. (A) (B) Different views of the plate and screws.
Note: 1: ilium region; 2: weight-bearing dome region; 3: posterior column; 4: posterior wall and medial quadrilateral region; 5: acetabular margin of posterior wall; 6: inferior region of acetabulum; 7: ischial branch region. P1: positioning hole in the superior margin of the acetabulum; P2/P3: positioning hole in the inferior margin of the acetabulum.

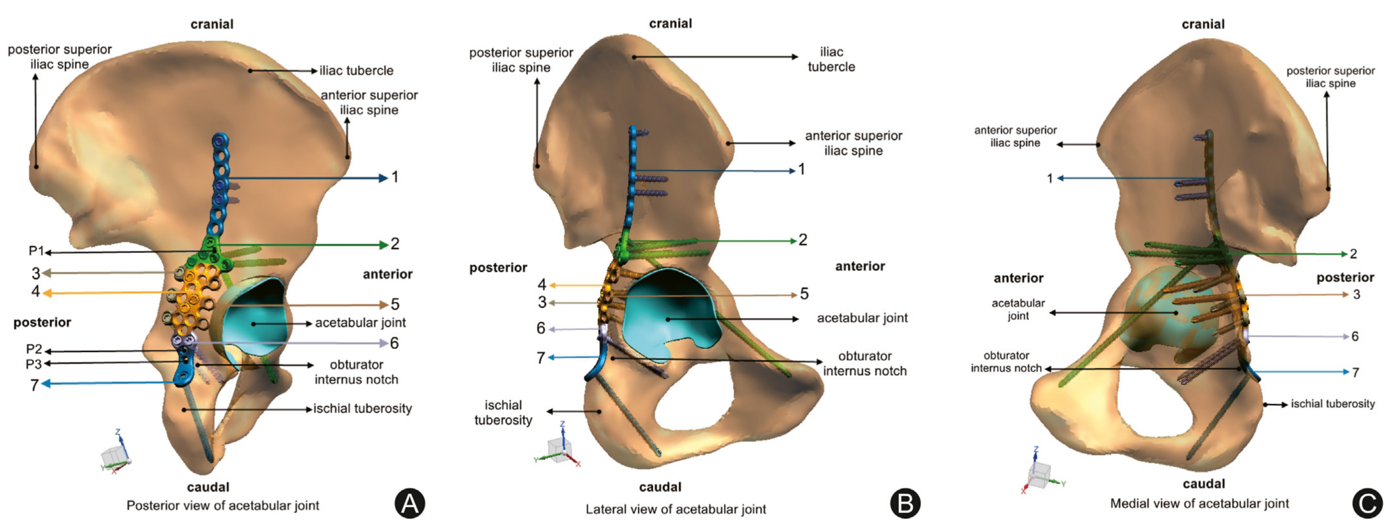

Fig. 2. Perspective view of plate and screws implanted in pelvis. Screws can be fixed in the superior and inferior, posterior and anterior, and medial quadrilateral regions of the acetabular joint (A-C).
Note: PSIS: posterior superior iliac spine; ASIS: anterior superior iliac spine; OIN: obturator internus notch; AJ: acetabular joint.

research,[15] the apparent bone density ρ_{app} is calculated using the following formula:

$$\rho_{app} = \left\{ 1.9 \times 10^{-3} \times \overline{Hu} + 0.105\ \overline{Hu} \right.$$

$$\leq 8167.69 \times 10^{-4} \times \overline{Hu} + 1.028\ \overline{Hu} > 816$$

The unit is g/cm^3. According to Carter's research,[16] the bone elastic modulus E = 2875 × ρ_ash^3 (MPa), and the Poisson's ratio is 0.3. According to Phillips research,[13] the material properties of the seven ligaments are shown in Table 1.

The six directions of displacement are as follows: the X direction is the sagittal plane, the Y direction is perpendicular to the sagittal plane and turn to the left, the Z direction is perpendicular to the coronal plane and forward.

Boundary conditions and validation of model

The reference point established above the S1 vertebral body is distribution coupling with all the unit nodes on the upper edge of

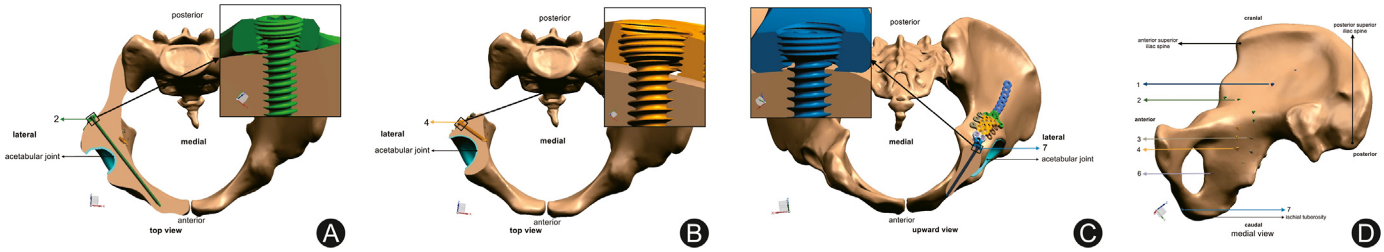

Fig. 3. Cross-sectional view of longitudinal axis of screw. Seven functional fixation zones of PASP are divided and defined by different colors. The small figures show different locking angles of the screw. (A) The 2nd functional fixation zone in weight-bearing region; (B) The exit position of screws on medial quadrilateral region; (C) and (D) The 4th and 7th functional fixation zone.

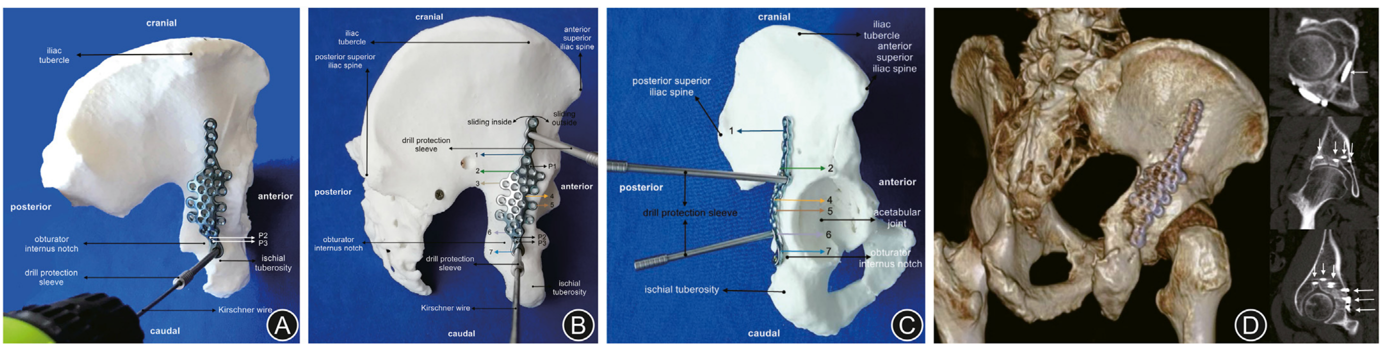

Fig. 4. Plate implantation in pelvis. (A) Kirschner wire was inserted in the caudal end of the plate (the 7th zone) by the drill protection sleeve. (B) Fix the caudal end of the plate so that the cranial end can slide inside or outside (indicated by the arrow) for the best position. (C) Side view shows that the plate curvature matches the posterior surface of the acetabulum. (D) Pelvic CT shows that the plate is in proper position, and the screw distribution is reasonable in transverse, coronal and sagittal plane.
Note: Vertical arrows indicate screws of zone 2; horizontal arrows indicate screws of zone 3 and zone 4.

the S1.[17] In order to simulate the human sitting posture and the movement states of turning right/left, six directions of bilateral ischial tuberosity in XYZ triaxis were constrained. A load of 600 N (equivalent to 60 kg body weight) was applied to the reference point along the direction of gravity, and a torque of 8 N·m was applied to the right and left directions respectively for a period of 1 s. Model verification was performed in software Abaqus 6.9 (Dassault Systemes SIMULIA Corp., USA). It showed that the stress was mainly distributed through the sacrum, sacroiliac joint, arcuate line, posterior column and ischial tuberosity (Fig. 5) with the normal sitting position. The displacement distribution was similar to waves (Fig. 5) which was consistent with previous literature reports.[18–22] From blue to red, the distribution nephogram values gradually increase.

Fracture model and internal implant assembly

According to the morphological characteristics described by OTA classification type 62C1,[11] the model of left both-column acetabular fracture was established. There were three fracture fragments in the anterior and posterior columns respectively, and acetabular joint was not connected to the axial sacrum. The sacrospinous ligament and sacrotuberous ligament on the left were missing.

According to the requirements of clinical surgery, three kinds of implants — PASP, DRP, and anterior CRP — were assembled on this model. Each kind of implant was assembled with 8 screws of 3.5 mm diameter for homogeneousness comparison. The nine points of stress and displacement measurement are: 1. Right iliac fossa, 2. Left iliac fossa, 3. Right sacral ala, 4. Left sacral ala, 5. Right arcuate line, 6. Left arcuate line, 7. Right pubic tubercle, 8. Left pubic tubercle, and 9. Sacral promontory (Fig. 5B).

Von Mises stress patterns were used for stress analysis of various parts of the implants. The peak stress of implant indicates that the risk of metal fatigue rupture is likely to occur. The peak displacement represents the largest movement distance of the plate or screw, which are prone to implant loosening. The numbers of total nodes were 103178, 135895 and 121593 in PASP, DRP and CRP models respectively and total number of elements were 329974, 522867 and 440046 respectively.

Table 1
Material properties of the seven pelvic ligaments.

	Ligament name	Spring stiffness (N/mm)	Attachment area (mm^2)	Number of units
1	Sacroiliac ligament	5000	1391	525
2	Sacrospinous ligament	1500	112	12
3	Sacrotuberous ligament	1500	539	56
4	Iliolumbar ligament;	1000	506	50
5	Inguinal ligament	250	45	9
6	Superior pubic ligament	500	97	10
7	Arcuate pubic ligament	500	156	15

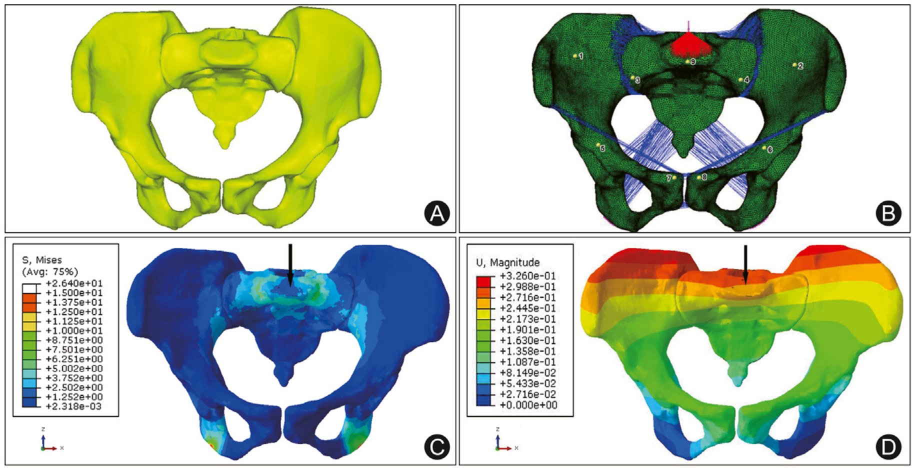

Fig. 5. (A) Pelvic solid model; (B) Finite element model of the pelvis and its seven ligaments with 9 measurement points. Model validation, stress (C) and displacement distribution (D) of the sitting posture under a vertical load of 600 N.

Results

The load is positively correlated with stress and displacement, which is consistent with relevant literature reports.[18] The stress and displacement of three types of implants under three kinds of loads are analysed as follows (Fig. 6).

Under three kinds of loads, the peaks of stress all reached when turning to the right, respectively 313.5 MPa, 383.0 Mpa, and 442.4 MPa for PASP, DRP, and CRP.

Under the three loads, the displacement peaks of PASP and DRP were 1.15 mm, 1.26 mm respectively, when turning right. The displacement peak of CRP occurred when turning left. The order of stress and displacement peak values under three kinds of loads was CRP > DRP > PASP.

It can be seen from Fig. 7 that the order of the stress and displacement peak value under three kinds of loads was CRP > DRP > PASP. When turning left, the peak values of PASP and DRP were less than that of turning right. The stress impact and displacement on CRP was basically the same under three loading conditions.

Discussion

The peak displacement and stress of PASP are the minimal compared with CRP and DRP (Fig. 7), which indicates that PASP has the best stability and is least prone to implant failure. Its clinical importance is that PASP can be used to replace CRP or DRP in operation to provide higher stability.

In the phase of turning left, the peak stress and displacement on DRP and PASP decreased with the increase of time (Fig. 7), which indicates that this movement can maintain the stability of internal fixation and the implant is not easy to loosen or rupture. The clinical significance is that it is safe to turn the ipsilateral side after operation for both-column fracture cases with posterior plate fixation. It can be conjectured that the ipsilateral rotation of the posterior plate fixation can reduce the implant failure. Under three kinds of loading conditions (Fig. 7), the changes of stress and displacement of CRP are minimal, indicating that the effects on implants are basically the same. Its clinical significance is that it is safe to turn to both sides after CRP fixation.

To the best knowledge of the authors, no biomechanical research data of postoperative movement after internal fixation of both-column acetabular fractures is available in the literature. There are no finite element studies of pelvis and its adjacent abdominal and spinal muscles.[13] Due to the complex morphology of both-column acetabular fractures, it is difficult to establish a biomechanical finite element model. The current biomechanical finite element study of acetabular internal fixation has two limitations: (1) inaccurate description of fracture morphology, and (2) not already defined width and thickness of the plate as well as diameter & length of screws, resulting in low comparability of experiment.[18,23,24] Biomechanical studies have shown that the stress on the weight-bearing area of acetabular dome is the most concentrated, which requires anatomical reduction and effective fixation.[21,22] If the implant cannot effectively fix the displaced articular fragments, postoperative movements will result in reduction loss, implant loosening or rupture. The articular surface is not smooth, and the friction between the femoral head and the acetabular cartilage surface will cause traumatic arthritis, which requires THR.

PASP provides a new posterior fixation technique for acetabular fractures, which is designed according to the principles of tension band, pressure band, and load sharing.[25] The shape of the plate is basically consistent with the distribution area of the pression and tension trabeculae of the acetabulum, which can reasonably disperse the compressive and tensile stress of the hip joint and conforms to the mechanical conduction path of the acetabulum bone. It bears the movement load of the hip joint and helps the fracture to heal stably in the most beneficial way for the patient, which meets the requirements of enhanced recovery after surgery.

Compared with multiple reconstruction plates fixation, this technique can reduce the peeling injury of soft tissue during operation. Through a single posterior approach, PASP can simultaneously fix the fracture fragments of the superior and inferior, anterior and posterior, and medial regions of the acetabular joint (Fig. 2). Therefore, it can avoid anterior acetabular fixation and reduce the amount of fixed plates and surgical trauma. The use of a drill protection sleeve ensures the safety of screw insertion and improves surgical efficiency. It can save the time of reconstruction plate shaping during operation, thus reducing operation time and wound exposure time, and blood loss. PASP is helpful to complete the procedure safely and effectively.

The limitations of this study are simulated bone and ligament damage, and the stability offered by the surrounding muscles was

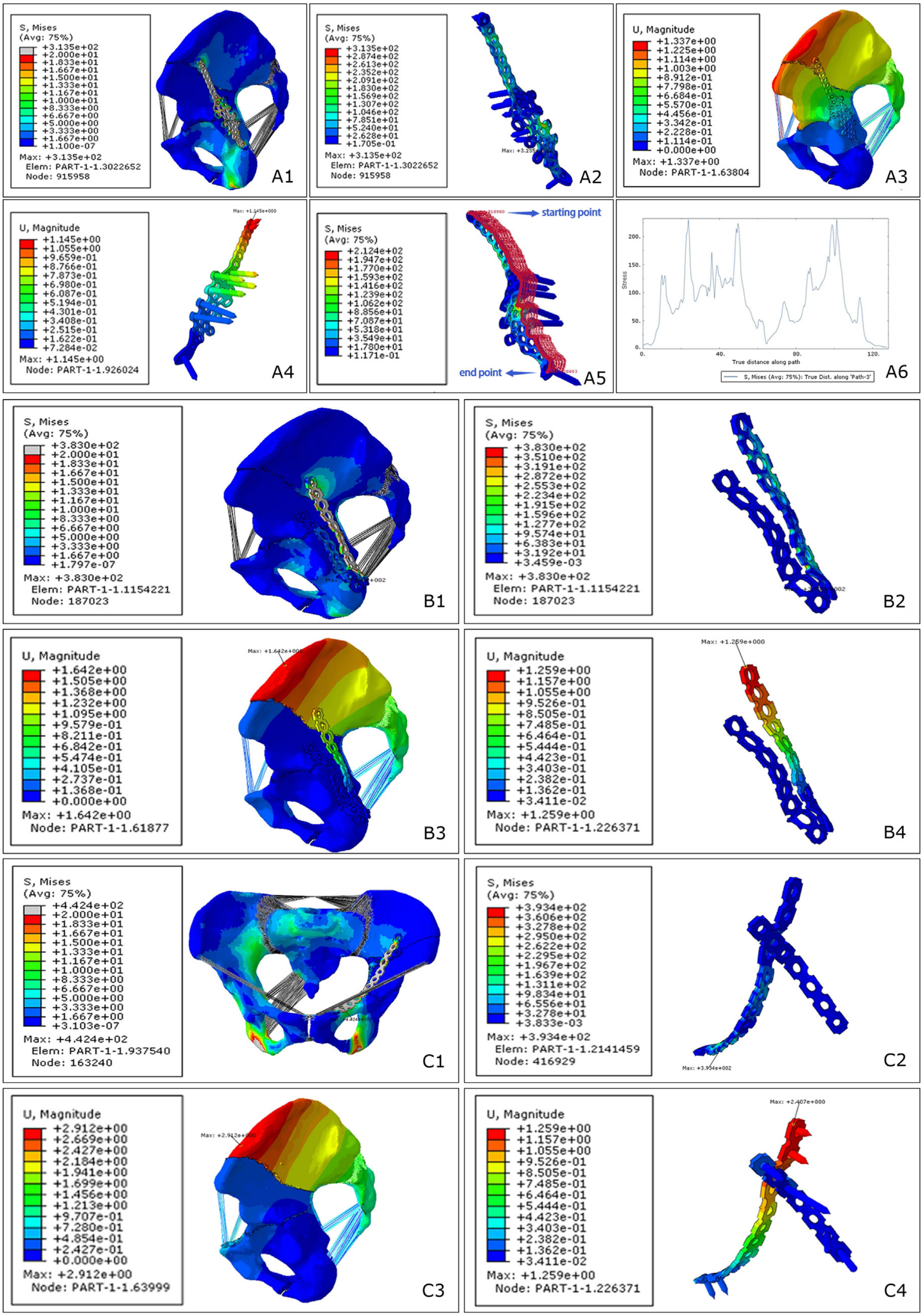

Fig. 6. (A1, A2) Stress nephogram of turning right in PASP; (A3, A4) Displacement distribution nephogram of turning right in PASP; (A5) Stress conduction of PASP; (A6) The stress curve of PASP when turning right. In the Figs. A5 and A6, the arrows indicate three stress concentrated positions of PASP. (B1–B4) Stress and displacement distribution nephogram of turning right in DRP; (C1, C2) Stress nephogram of turning right in CRP; (C3, C4) Displacement distribution nephogram of turning left in CRP.

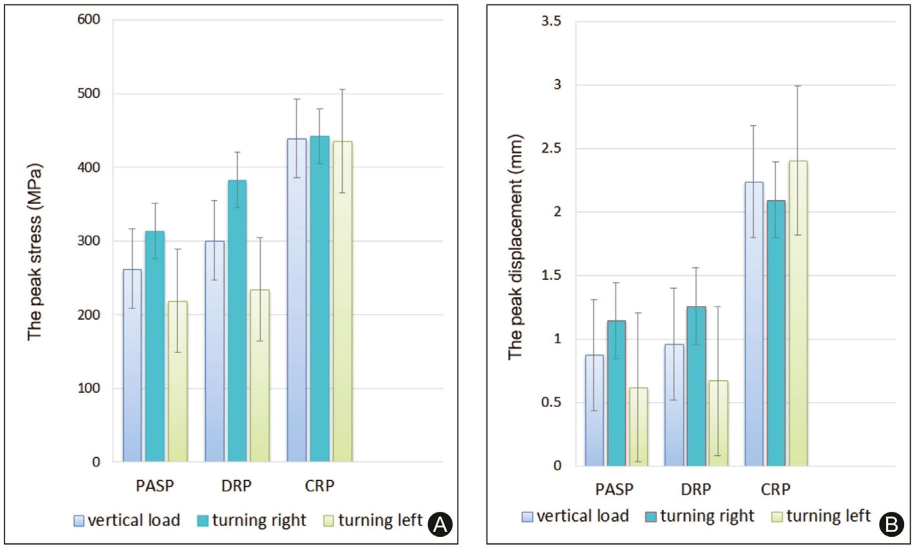

Fig. 7. The peak stress (A) and displacement (B) of three types of internal fixations for both-column acetabular fractures.

ignored. But, this technical limitation affected all the groups equally. However, further studies are needed to explore the walking motion on the stability of internal fixation in future research work.

In conclusion, the use of PASP instead of two reconstruction plates can provide higher stability for both-column acetabular fractures. The rational postoperative movement after posterior plate fixation of acetabular fracture is to turn to the ipsilateral side, which can reduce the implant failures.

Funding

Nil.

Ethical statement

This study has been approved by local ethics committee (Approval No. L2018013).

Declaration of competing interest

The authors own all rights and interests for this patent.

Author contributions

Ming Li: design of this study and draft of the manuscript; Shuai-Yi Wang: manuscript preparation; Jing-Wei Xiao: participation in the design of the study. All authors reviewed and confirmed the final manuscript.

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