Three-dimensional printing simulated operation combined with robot-aided minimally invasive lumbopelvic fixation in treatment of unstable bilateral sacral fractures: technical notes and 8 case series

Zhaojie liu
Tianjin Hospital https://orcid.org/0000-0002-2212-3672
Wei Tian
Tianjin Hospital
Xin Jin
Tianjin Hospital
Haotian Qi
Tianjin Hospital
Yuxi Sun
Tianjin Hospital
Yongcheng Hu
Tianjin Hospital
Jian Jia (hospitaljj@163.com)

Technical advance

Keywords: Three-dimensional printing, Robotics, Minimally invasive surgery, Lumbopelvic fixation, Unstable, Sacral fracture

Posted Date: April 13th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-21251/v1

Abstract

Background Despite their seldom appearance, unstable bilateral sacral fractures are severe injuries and always cause surgical management difficulties. Lumbopelvic fixation is reliable for rigid method, but wound-related complications with open procedure have been relatively common.

Methods Data of 8 patients with unstable bilateral sacral fractures who were treated surgically in our institution from March 2016 to April 2019 were retrospectively analyzed. There were 5 men and 3 women with an average age of 38.5 years (range, 19-60years). According to the sharp of sacral fractures, there were one case with simple bilateral vertical fracture lines, 6 cases with “U” and one case with “H”. According to Roy-Camille classification, 7 of 8 sacral fractures involving sacral canal were classified with type I 2 cases, type II 4 cases and type III 1 case. Three-dimensional(3D) printing pelvis were performed to simulate lumbopelvic and sacroiliac screw fixation for preoperative planning. Eight bilateral sacral fractures were treated with minimally invasive lumbopelvic fixation under robotic guidance.

Results The screws inserted with robotic assistance were exposed to radiation with an average of 41.6±10.2 times (range, 27–53 times) intraoperatively. The total fluoroscopy time was 32–59 s, and the average fluoroscopy time for each screw was 4.2±0.6s. According to modified Gras classification of screw position, there were Grade I in 7 cases and Grade II in one case (left S1 screw). The average operation time was 150.6 min (range, 95-220 min), and intraoperative blood loss was 87.5 ml (range, 60-120 ml). Eight patients were followed up consecutively for at least 12 months, with an average of 17.0 months (range, 12–24months). No patient suffered a neurovascular injury intraoperatively. There were no incision-related complications. All fractures healed with an average time of 4.2 months (range, 3–10 months). According to Majeed functional assessment investigation, the mean score was 88.4 points (range, 78–98 points), which were graded as follows: 5, excellent and 3, good.

Conclusion Under robot guidance, minimally invasive lumbopelvic fixation for unstable bilateral sacral fractures is a feasible option with the advantages of accuracy, less radiation and safety. Simulated operation with 3D printing for preoperative planning can simplify the actual surgery.

Background

Unstable bilateral sacral fractures frequently occur in high energy traumas after falling from height, which belong to severe injuries with high mortality due to concomitant injuries and the following complications. The main mechanism of injury lies in vertical shear which usually causes a bilateral intra-foraminal fracture resulting in extreme instability of the spinopelvic area. Additionally, the stress provokes the sacrum to pivot out of the posterior pelvic ring simultaneously, which creates a horizontal fracture, normally in the S1 to S2 junction, known as a weak area in the bony structure of the sacrum [1]. The sacral fractures can be mainly manifested as U-, H-, or Y-shaped patterns in these injuries. The inferior part of the sacrum is attached to the posterior pelvic ring, which stays intact while the superior part is attached to the spine. Therefore, these severe injuries are also known as spinopelvic dissociation.

The purpose of surgical fixation is reconstruction of the lumbopelvic area to avoid the malunion and allow early weight-bearing. The trans-iliac plate [2, 3], sacroiliac screws [4, 5], and trans-iliac rods fixation [6, 7] can be optimal options for posterior pelvic ring injuries, but they are unable to stabilize the lumbopelvic junction. Since Galveston technique was proved to provide good reduction and sufficient strength for bilateral sacral fractures with vertical instability, lumbopelvic fixation has been modified continuously. In addition, combined with bilateral S1 cannulated screws, lumbopelvic fixation can better maintain the rotation stability of sacral fracture end [8].

However, wound-related complications are relatively common due to excessive exposure. For the past few years, minimally invasive surgery, as the major development trend of modern orthopedics, has overcome the shortcomings of conventional open surgery, such as more invasiveness and more bleeding [9]. With the development of artificial technology, minimally invasive internal fixation with computer and robot navigation has been increasingly applied in clinic. Compared with the non-navigation surgery, this method, especially the robot-aided technology, shows significantly better accuracy on screw positioning and less radiation damage [10–12]. Therefore, it has been accepted by an increasing number of orthopedic surgeons and promoted in clinical practice.

Nevertheless, preoperative planning is also critical for the success of surgery. Recently, the emergence of 3D printing model is of great significance to the development of orthopaedics surgery. Existing studies show that the surgical treatment of acetabular or pelvic fracture was completed more effectively by surgeons who took advantage of 3D printing technology [13–14]. In addition to patient-specific 3D printing external template [15], there is no doubt that the biggest advantage lies in the use of equal proportion printing model for simulated operation, which can confirm the ideal sequence of fracture reduction and fixation or the osteotomy site, and determine the optimal position of the implants.

In view of this, we applied the above technology combination for the treatment of unstable bilateral sacral fractures. The purpose of this study is to report our preoperative planning, technique and experience, and to evaluate the clinical and radiological results.

Patients And Methods

We reviewed all patients with unstable bilateral sacral fractures treated in our department from March 2016 to April 2019 and identified twenty patients. Inclusion criteria were: (1) unstable bilateral sacral fractures of which duration from trauma to surgery was less than 3 weeks, (2) treated with lumbopelvic fixation associated with sacroiliac screws under robotic guidance, (3) patients whose epiphysis was closed. Exclusion criteria were: (1) sacral fractures associated with cauda equina neurologic deficits need to be decompressed, (2) patients with severe thoracic or craniocerebral trauma who could not tolerate on a prone position, (3) vestibular deformity or mal-reduction of S1 which is not enough to pass through a cannulated screw with the diameter of 6.5 mm, (4) transverse fracture line which is located at S1 vertebra.

Twelves patients were excluded because of the exclusion criteria. Eight of them associated with cauda equina syndrome which need to be decompressed via open approach, three of them were treated with open reduction and internal fixation because duration from trauma to surgery was more than three weeks. One case was treated conservatively because of severe craniocerebral trauma. According to the inclusion and exclusion criteria above, eight patients were enrolled in this study (Table 1).

Table 1
Clinical data of cases in our study group

NO.	Age	Gender	Type of trauma	Classification		Disruption of the anterior pelvic ring	Duration from trauma to surgery(days)	Operation time(min)	Blood loss(ml)	Follow-up (months)	Clinical outcome
				Gibbons	Denis						
1	23	M	Suicidal jump	II	III	Yes	4	110	90	22	excellent
2	13	M	Suicidal jump	II	III	Yes	10	200	110	24	good
3	37	F	Accidental fall		III	No	5	95	70	12	excellent
4	54	M	Accidental fall	II	III	No	7	125	100	15	excellent
5	53	M	Suicidal jump		III	Yes	20	220	120	14	good
6	42	F	Accidental fall	II	III	No	8	180	60	20	excellent
7	35	F	Suicidal jump		II	Yes	7	120	70	12	good
8	39	M	Car accident		III	No	7	155	80	17	excellent

This retrospective study protocol was approved by Medical Ethics Committee in our institution, and written Informed consent was obtained from all participants included in the study.

The average age at the time of trauma was 38.5 years (range, 19–60 years). There were 5 men and 3 women, with an average Injury Severity Score of 26 (range, 16–38). The Type of trauma included the following: falling or jumping from height (seven patients) and being involved in a car accident (one patient). Seven sacral fractures were type III and one was type II which has been classified by Denis [16]. According to the sharp of the sacral fractures, there were one case with simple bilateral vertical fracture lines, six cases with “U” and one case with “H”. Except one case without transverse fracture line on sacrum, seven of eight sacral fractures that involved sacral canal were classified with type I in two cases, type II four cases and type III one case on the basis of Roy-Camille classification [1]. According to Gibbons classification [17] of neurologic deficits, there were three cases combined with sacral nerve injury of grade II. Of the eight cases with unstable bilateral sacral fractures, four cases combined with pubic ramus fractures and one case with transverse acetabulum fracture.

Patients with unstable hemodynamics were treated with blood volume expansion therapy after admission. Femoral condyle skeletal traction was undergone bilaterally except the nondisplaced sacral fracture. Once the general condition was sufficiently stable, routine images such as X-ray, CT scans, and 3D reconstruction were obtained and concomitant injuries were treated urgently and continuously in necessary (Fig. 1a-d). We measured bilateral vestibular anatomy of S1 with CT scans to exclude developmental deformity and to determine if a cannulated screw with the diameter of 6.5 mm can pass through. According to CT data, 3D model with equal proportion was created printed, and then simulated operation was performed (Fig. 2a-b). On one hand, we ensured the precise entry point and position of the screws and robs with 3D printing models. On the other hand, the required fracture reduction degree was determined by preoperative planning so as to achieve the anatomical reconstruction more easily during the surgery. Additionally, the individual projection angulation of inlet and outlet views were confirmed with X-ray images for the convenience of actual operation. After surgical feasibility had been manifested, implants were removed and recorded to guide the intraoperative application (Fig. 3a-d). Finally, ultimate surgery, minimally invasive lumbopelvic fixation combined with sacroiliac screws under robotic guidance, was performed according to the preoperative planning (Fig. 4 Management algorithm).

The timing of surgical treatment, operative time and estimated blood loss were recorded. Immediate postoperative X-ray and CT scans were reviewed to evaluate the reduction and hardware position. Maximum residual displacement in various directions were recorded and graded according to the imaging standard of Mears and Velyvis [18]. The reduction qualities of pelvic fractures were classified as follows: extremely satisfactory reduction (anatomical reduction), satisfactory reduction (vertical and / or horizontal displacement < 1 cm and / or rotation < 15 °), and unsatisfactory reduction (vertical or horizontal displacement > 1 cm and / or rotation > 15 °). A modified Gras classification was applied to assess the positioning of pedicle and sacroiliac screws under CT visualization [19]. The classification of the screw placement positioning on the tomographic image of CT scans consisted of a three-grade score: Grade I, secure positioning, completely in the cancellous bone; Grade II, secure positioning, but contacting cortical bone structures; Grade III, misplaced positioning, penetrating the cortical bone. Follow-ups were routinely scheduled at 6-week, 3-month, 6-month, 1-year and thereafter 1-year intervals postoperatively. The function outcomes were evaluated with Majeed's scoring system [20], and clinical outcome was graded as follows: excellent (85–100), good (70–84), fair (55–69), and poor (< 55). Anticoagulation was used from the admission until patient was able to get out of bed. Patients began weight bearing 6 weeks after surgery.

Surgical Equipment And Instrument

The TiRobot system, the third generation TianJi robot for orthopaedic surgery (TINAVI Medical Technologies, Beijing, China), is composed of a main console, surgical planning and controlling software, an optical tracking system, a robotic arm with six joints, a main control workstation, and a navigation and positioning toolkit. Additional surgical equipment included a C-arm X-ray and CT machine (Siemens, Germany), φ6.5-mm cannulated screw, φ7mm polyaxial iliac screw and φ6-mm polyaxial pedicle screw systems (Kanghui Medical Instruments, China).

Surgical Procedures

All procedure were performed by a group of orthopedic surgeons with rich experience.

The patients were administered general anesthesia with tracheal intubation after being placed with the prone position on a radiolucent table. Draping began from the mid thoracic spine to above the natal cleft, including both flanks laterally. Intravenous antibiotics were administered within 30 minutes of the skin incisions.

Pelvic anteroposterior, inlet, outlet and Judet views were obtained using the image intensifier to identify feasibility of these images preoperatively. First, a navigation tracker was fixed on L3 spinous process percutaneously. After L5 initial intraoperative CT images were obtained using a C-arm machine, they were transmitted to the robotic planning system. Based on preoperative planning combined with L5 vertebra anatomic feature, the length, angulation and direction of bilateral pedicle screws were designed and the simulation of the screw placement was completed on the images (Fig. 5a). Then a sterile working environment for the robotic arm was established by assembling and fixing the locator and the sterile protective sleeve. After the navigation planning was established, the robotic arm began to move following the guidance in the preplanned trajectory outside the body. Next, the sleeve was placed onto the bone surface via a percutaneous incision and a guide pin was inserted into the pedicle after the trajectory was recalibrated (Fig. 6a). Furthermore, a cannulated polyaxial pedicle screw 6 mm in diameter was inserted along the pin. Finally, the contralateral same screw was inserted in the same way.

After the pedicle screws were fixed, the bilateral posterior superior iliac spines (PSIS) were exposed subperiosteally through 3 cm incisions. Next, we resected part of PSIS to avoid skin irritation caused by protruding screws, and then inserted a polyaxial iliac screw 7 mm in diameter 10 cm deep on each side. Meanwhile, we had to make sure that the direction was from PSIS to anterior inferior iliac spine (AIIS) and between the medial and lateral lamina of the iliac wing. Then the bilateral pre-contoured rods with the diameter of 6.5 mm were inserted

subfascially and connected to the pedicle screw and iliac screw. Once the bilateral vertical and rotational displacement was corrected through the distraction of the lumbopelvic devices with reduction clamps, all connectors were fixed rigidly (Fig. 6b). The reduction quality of the posterior pelvic ring fracture was manifested intraoperatively with C-arm fluoroscopy.

The last part of management of the posterior pelvic ring was the insertion of bilateral S1 sacroiliac screws. After the navigation tractor was then fixed to PSIS, intraoperative anteroposterior, inlet, outlet and Judet views of the pelvis were obtained and transmitted to the robotic planning system again. Then the angulation and direction of bilateral sacroiliac screws were designed and the simulation of the screw placement was completed on the images. With the guidance in the preplanned trajectory, the sleeve carried by robotic arm carrying moved to target area. A guide pin was drilled into sacrum via a percutaneous incision after the trajectory was recalibrated (Fig. 5b). Finally, a cannulated sacroiliac screw with a diameter of 6.5 mm was inserted into S1 vertebra along the pin on each side. After the reduction and fixation were checked again with fluoroscopy, the skin and subcutaneous tissues were sutured (Fig. 6c and Fig. 7a-c).

Postoperative Management

All patients underwent the same management with intravenously administered antibiotics postoperatively continued for 24 hours. Low-molecular-weight heparin (LMWH) was used for deep venous thrombosis prophylaxis during hospitalization. Patients were encouraged to use wheelchairs for mobility 2 weeks after surgery. Partial weight bearing was initiated usually 4 weeks and full weight bearing was permitted 8 weeks after surgery. However, the details about weight-bearing activity should also be considered depending on the recovery of concomitant injuries.

Results

All cases were treated with minimally invasive lumbopelvic fixation under robotic guidance between days 4 and 20 (mean, 8.5 days) after initial injury. The average surgical time was 150.6 min (range, 95–220 min), with intraoperative blood loss of 87.5 ml (range, 60–120 ml). No patient suffered a neurovascular injury intraoperatively. No incision infection, fat liquefaction, irritation in iliac spine about prominent implant and other incision-related complications occurred postoperatively. Eight patients were followed up consecutively for at least 12 months, with an average follow-up period of 17.0 months (range, 12–24months). Secondary loss of reduction or hardware failure did not occur during the follow-ups. All sacral fractures healed in an average time of 4.2 months (range, 3–10 months). Seven of eight cases underwent hardware removal between 12 months and 18 months after surgery, while we had offered all patients to remove implants. The other one patient did not want to have his implants removed because of his advanced age. Three cases with sacral nerve injury were improved from Gibbons grade II to grade I without residual neurological symptom after conservative treatment with oral neurotrophic drugs.

Accuracy Evaluation

All eight patients were bilaterally stabilized with lumbopelvic fixation combined with a total of 16 sacroiliac screws (1–1 SI screws in each case). Transverse fracture of the acetabulum in one case was fixed percutaneously with cannulated screws under robotic guidance because of non-displacement. Four cases with unilateral fractures of pubic ramus were treated conservatively.

The screws inserted with robotic assistance were exposed to radiation with an average of 41.6 ± 10.2 times (range, 27–53 times) intraoperatively. The total fluoroscopy time was 32–59 s, and the average fluoroscopy time for each screw was 4.2 ± 0.6 s.

Postoperative X-ray images and computed tomography (CT) scans showed that all the pelvic rings were in good shape and there was no incidence of screw perforation (Fig. 8a-e). According to modified Gras classification on screw positioning [19], there were Grade I in 7 cases and Grade II in one case (left S1 screw). The positioning of pedicle and sacroiliac screws planned intraoperatively using the robot system and actual positioning of screws demonstrated from postoperative CT scans were compared to evaluate the accuracy of the robotic navigation. The positioning error and the angular error were 2.12 ± 1.03 mm and 4.15 ± 1.74°, respectively. According to the imaging standards given by Mears and Velyvis [18], the radiological results evaluated with postoperative X-ray images and CT scans showed anatomical reduction in 7 cases and satisfactory reduction in one case.

The satisfactory reduction case was revealed that the residual deformity was 5 mm in vertical displacement whereas horizontal or rotational displacement was corrected. A total of eight patients completed the Majeed [20] functional assessment investigation at their last follow ups. The mean score was 88.4 points (range, 78–98 points), which were graded as follows: 5, excellent and 3, good.

Discussion

Bilateral sacral fractures essentially separate the lower lumbar spine from the pelvis, which usually occur secondary to high-energy trauma. Disruption of the posterior pelvic ring causes a multi-directional instability of lumbopelvic area with a possible rotational, vertical, and translational displacement, depending on the direction of applied external force [21]. The treatment purpose is to reconstruct the spinopelvic stability with feasible methods. However, the surgical indication and fixation technique need to be considered on a case-by-case basis.

Nork [22] reported successful use of percutaneous sacroiliac screws for these kind of injuries like U-shaped sacral fractures with non-comminution and non-displacement. Other authors have recommended that lumbopelvic fixation technique is more suitable for patients with the comminuted, displaced and unstable sacral fractures classified by Roy-Camille [23]. The technique could provide enough distraction to reduce and fix vertical shear fracture of bilateral sacrum, but it doesn't guarantee the rotational stability of the posterior pelvic ring. Triangular osteosynthesis is a unilateral lumbopelvic instrumentation combined with a horizontal fixation using a sacroiliac screw or a trans-iliac plate firstly described by Shildhauer [24], which has been reported with enough rigidity to stabilize Tile C1 posterior pelvic ring injuries. This method has been shown to be biomechanically superior to the other techniques. Therefore, we started treating bilateral sacral fractures with lumbopelvic fixation a few years ago, on the basis of which we added S1 sacroiliac screws [8]. In our opinion, the fixation strength for spinopelvic dissociation is enough to maintain the reduction and enable early weight bearing. Anterior pelvic rings in these injuries are often slightly damaged, and most of them are not displaced. Therefore, 4 cases with pubic ramus fractures were treated conservatively and all of them achieved bony union successfully.

Although the lumbopelvic fixation with open surgery can provide enough rigidity, the rate of wound healing disturbances as high as 26% is still a big problem due to invasive procedure [25]. In recent years, minimally invasive triangular osteosynthesis and lumbopelvic fixation in treatment of unilateral and unstable bilateral sacral fractures have been developed, respectively. The advantages of minimally invasive surgery in shortening operation time, decreasing intraoperative bleeding, especially reducing infection rate have been repeatedly reported [9, 10, 26, 27]. Koshimune [28] compared conventional open lumbopelvic fixation with minimally invasive procedure for unstable bilateral sacral fractures. Infection occurred in 3 of 8 cases with the conventional method, and in none of the 8 patients with the minimally invasive method. In our series, none of the eight cases had wound-related complications such as infection. This may be explained by the fact that we did not detach the paraspinal muscles because the pedicle screw placement was completed as minimally invasive as possible during the procedure. Furthermore, the close reduction was accomplished under C-arm fluoroscopy with distraction clamps as well as countertraction of the patient.

Preoperative planning is always essential for complicated injuries, especially pelvic and acetabular fractures. Recently, it has been shown that the preoperative planning of complicated fractures can be improved more effectively with 3D printing technology [13, 14]. In view of our experience about this group of cases, we summarize advantages with 3D printing model as follow. First of all, because of the irregular morphology of the pelvis, the model can assist surgeons understand the preoperative situation of complicated fractures more easily and classify them more accurately. Secondly, surgeons can perform the simulated operation with 3D printing equal proportion model, which is helpful for them to design the optimal preoperative planning. As for the eight cases, we determined the sequence of reduction and fixation, the most effective angle and length of screws and the optimal position of implants with simulated procedure, which provided useful technical tips in planning pelvic surgery.

In addition to the detailed preoperative planning, precise operation is also essential. Excessive drilling will affect the holding force of screws, thus reducing the stability of implants and increasing the failure risk. Using 3D fluoroscopic navigation when performing pelvic surgery is reported to be useful in evaluating screw position. The above disadvantages could be reduced with 2D- or 3D-fluoroscopic navigation, but the malposition rate of screw fixation for pelvic fractures ranges from 0–31%, demonstrating that there's still certain room to improve the technology [29–31]. What's more, too much radiation exposure to patients and surgeons will also cause great harm to their bodies.

Recently, the emergence of surgical robots provided surgeons with an innovative technology which has revolutionary impacts on intraoperative guidance. Some existing studies and reported cases are summarized that the accuracy of screw placement with robot-assisted technique was superior to the conventional free-hand technique [34–36]. Under robotic guidance, it is safe and effective to achieve the correct trajectory of pelvic screw with over 95% accuracy [37]. Furthermore, intraoperative radiation exposure decreased obviously under robotic guidance due to a reduced number of guide pin attempts. The TiRobot surgical location and navigation system is the third generation of surgical robot produced by Beijing TINAVI Medical Technologies, which is also the latest generation of orthopedic surgery robot system developed independently in China and recognized internationally. According to our experience, the setup of the TiRobot navigation system is not cumbersome. Once the technique is used skillfully, operative time will be greatly saved. However, guide pins still need to be manually drilled along the sleeve under the guidance of robotic arm. Although the deviation of the trajectory can be monitored during drilling, if the angle and direction of guide pin need to be adjusted, re-planning must be done to ensure that the pins are completely positioned in the bone tunnel from beginning to the end. The postoperative CT scans revealed that there was no screw perforation in all 8

cases. While compared with the planning path, the positioning error and the angular error in the actual operation were 2.12 ± 1.03 mm and 4.15 ± 1.74°, respectively. The screw positioning error is much better than 2.9 ± 1.7 mm reported by Takao who completed the surgery with 3D navigation, which proves the accuracy and reliability with robot-assisted technology [38]. However, a satisfactory reduction that restores the integrity and continuity of the bone tunnel is a prerequisite for screw placement, especially the sacroiliac screw tunnel. Robot-assisted reduction is still used in the primary stage and only applies for fractures occurred in extremities [39–41]. In addition, for patients with cauda equina neurologic deficits who need decompression, a small median incision can be combined with on the basis of this technique that we mentioned, which we are in the process of developing with.

In conclusion, our novel method of minimally invasive lumbopelvic fixation under robot guidance after preoperative planning with 3D printing simulated operation may be a feasible option for unstable bilateral sacral fractures, particularly in patients whose injuries are less than 3 weeks. Accumulation of cases is warranted to provide the necessary evidence to guide clinical practice.

Declarations

Acknowledgements

Not applicable.

Funding

There is no external funding source.

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Authors’ contributions

JJ made substantial contributions to perform the surgery, revised the manuscript and approved the final version of the article. ZJL made substantial contributions to design and manuscript and assist to perform surgery. WT and XJ made contributions to assist to perform surgery and the statistical analysis. HTQ and YXS participated in collecting the data and assessed the outcomes. YCH participated in designing the study and revised the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This retrospective study was approved by the Ethics Committee of Tianjin Hospital and signed written informed consent was obtained from all participants.

Consent for publication

All patients gave written informed consent for publication.

Competing interests

There are no competing interests to declare.

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Figures

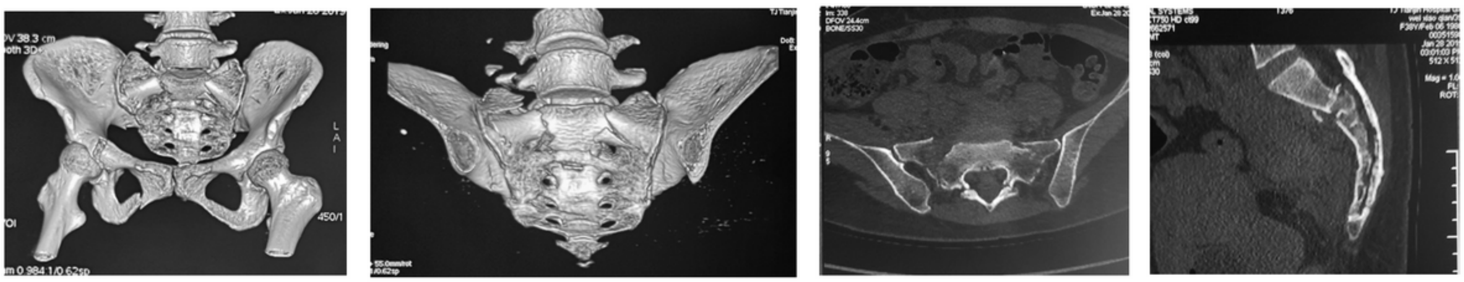

Figure 1

Female, 37-years-old, falling from height. a. CT reconstruction image on admission showing sacral fracture associated with unilateral fractures of superior and inferior pubic ramus; b. Enlarged image revealing a U-shaped sacral fracture with tilt displacement and L5 transverse process fracture; c. Axial CT view of S1 showing displaced sacral fracture associated with internal displacement of iliac wing on one side; d. Sagittal CT view of sacrum demonstrating the transverse fracture line was located at S2.

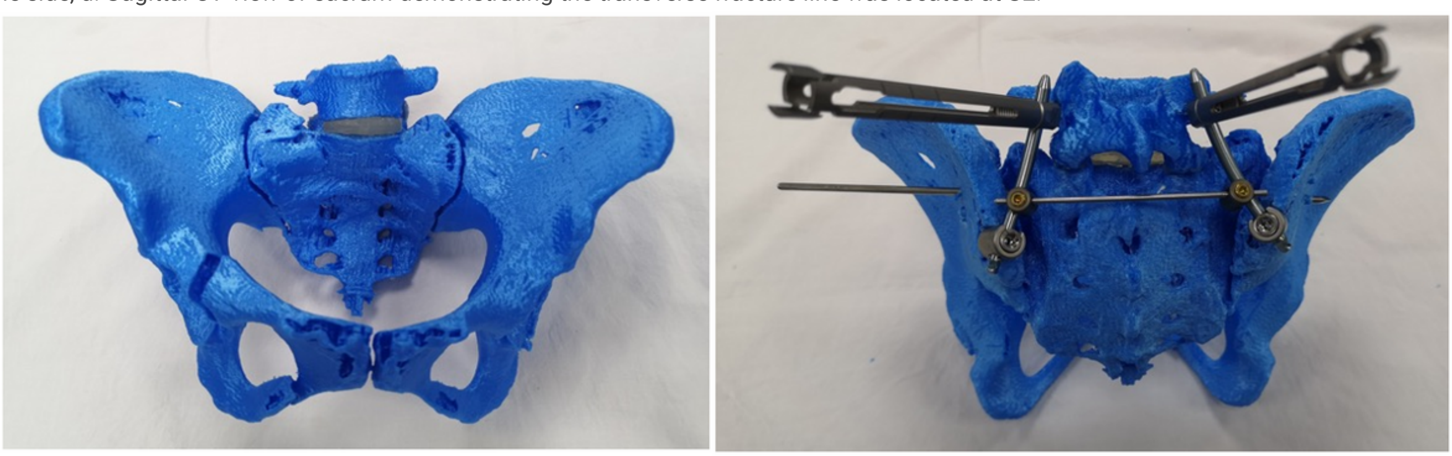

Figure 2

The simulated reduction and fixation on the model for the preoperative planning. a. 3D printing model of the pelvis is printed with gesso; b. Fixation with implants is simulated on the physical model of the spinopelvic area.

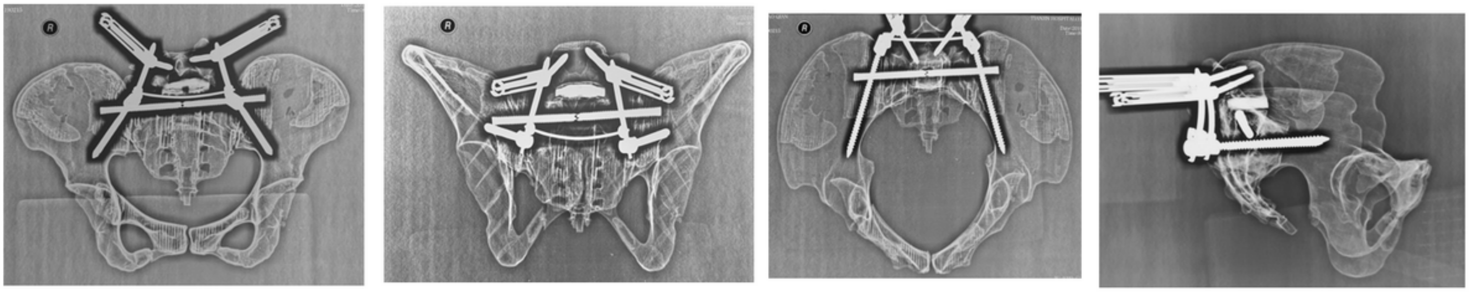

Figure 3

X-ray shows the position and orientation of implants with the preoperative planning. a. anteroposterior view. b. Inlet view. c. Outlet view. d. Lateral view.

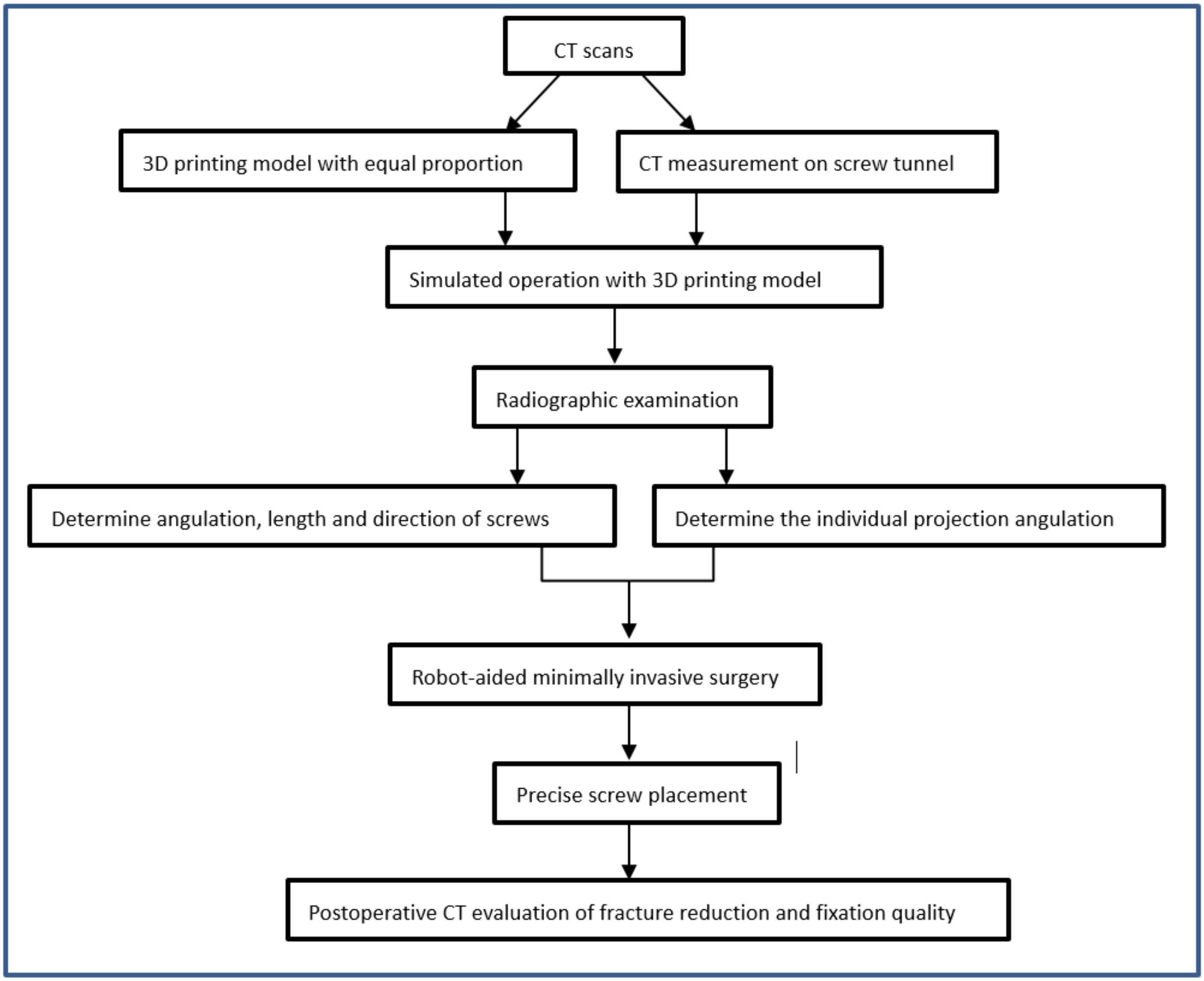

Figure 4

Management algorithm

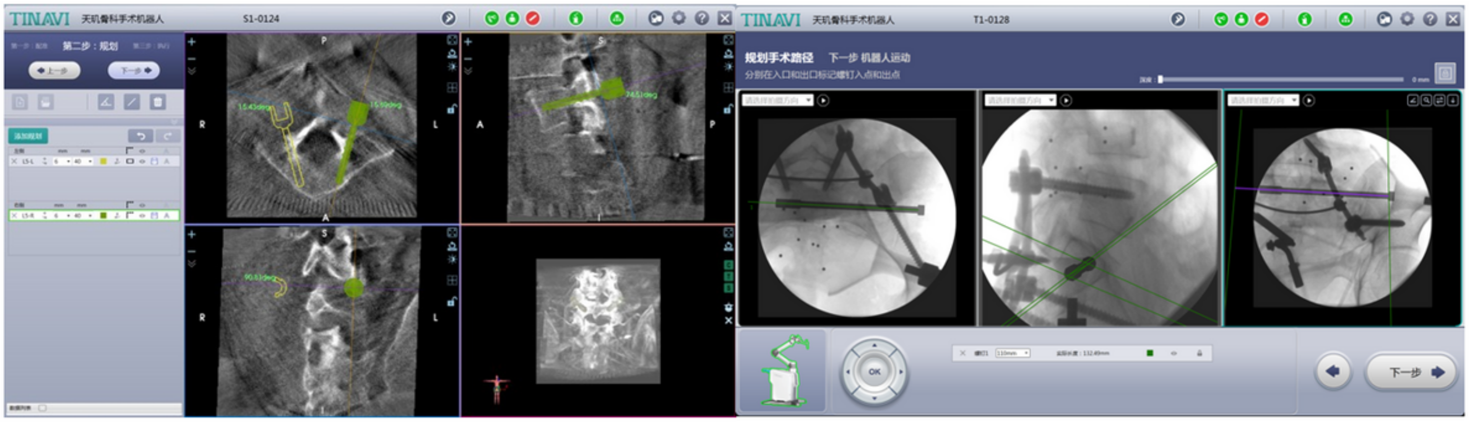

Figure 5

Robot-aided path planning after C-arm radiograph collection. a. Robot-aided path planning of bilateral pedicle screws placement in L5; b. Robot-aided path planning of bilateral sacroiliac screws placement in S1.

Figure 6

Intraoperative procedure and skin incisions. a. The guide pin insertion in L5 pedicle following the guidance of the robotic arm; b. Reduction with a distraction clamp to correct the vertical displacement of the sacral fracture after the screws and robs were inserted percutaneously; c. The length of each incision was less than 3cm, and they were placed symmetrically because of bilateral fixation with the same method.

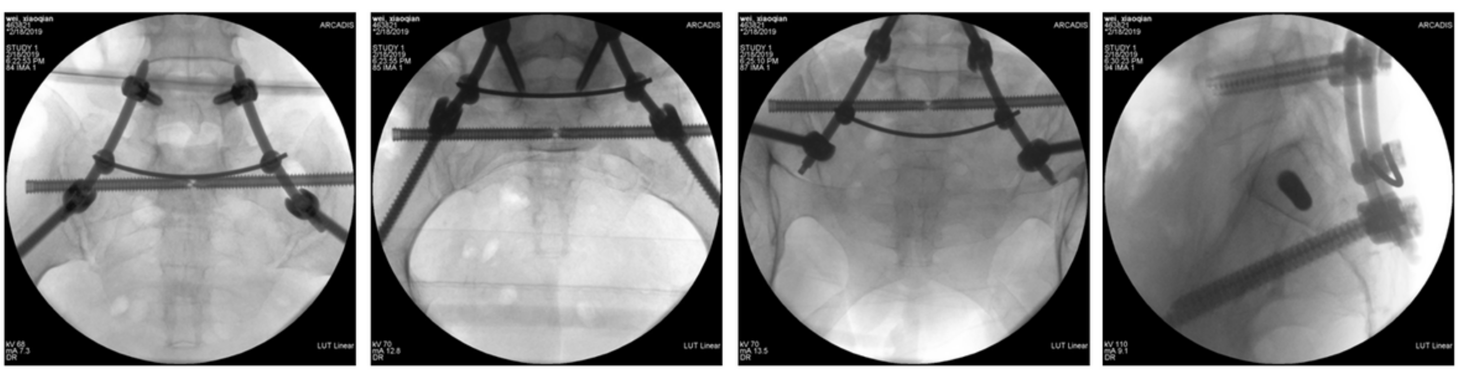

Figure 7

Intraoperative position and orientation of implants were consistent with the preoperative planning. a. anteroposterior view; b. Inlet view; c. Outlet view; d. Lateral view

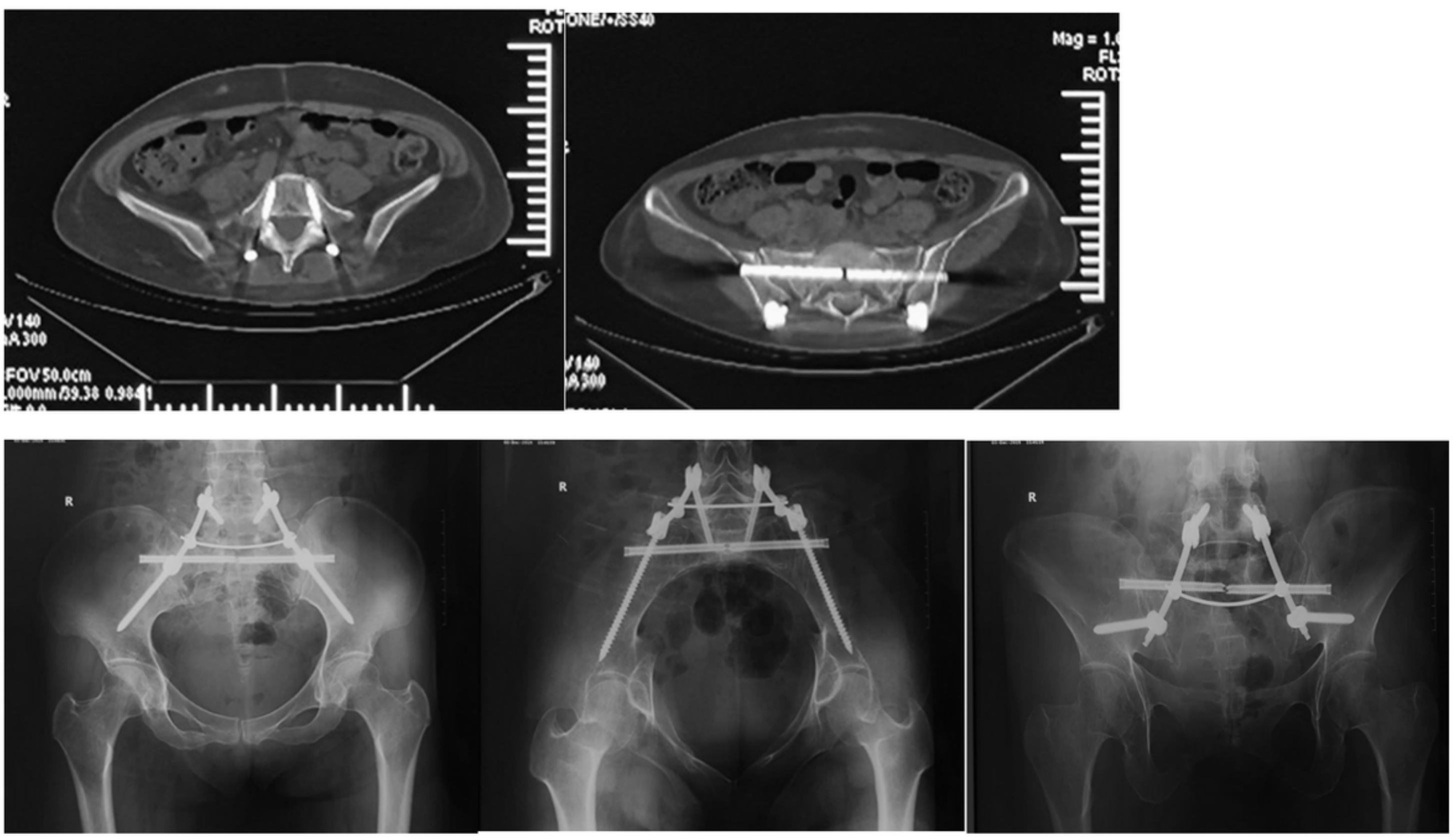

Figure 8

Postoperative images a. Postoperative axial CT view of L5 showing appropriate insertion of bilateral L5 pedicle screws; b. Postoperative axial CT view of S1 showing appropriate insertion of bilateral S1 sacroiliac screws; c-e. Radiographs of anteroposterior view, inlet view and outlet view after one-year follow-up showing posterior pelvic ring was stabilized by lumbopelvic fixation with bilateral S1 sacroiliac screws and all fractures healed.