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CLINICAL ARTICLE

# Robot-Aided Minimally Invasive Lumbopelvic Fixation in Treatment of Traumatic Spinopelvic Dissociation

Zhao-jie Liu, MD, Yong-cheng Hu, MD, Wei Tian, MD, Xin Jin, MD, Hao-tian Qi, MM, Yu-xi Sun, MM, Jian Jia, MD

*Department of Orthopaedics, Tianjin Hospital, Tianjin, China*

**Objective:** To investigate the surgical strategy, safety, and efficacy of close reduction and robot-aided minimally invasive lumbopelvic fixation in treatment of traumatic spinopelvic dissociation.

**Methods:** Data of 32 patients (21 males and 11 females) with traumatic spinopelvic dissociation treated by lumbopelvic fixation with robot-aided minimally invasive technique or conventional open procedure in our institution from March 2010 to April 2019 were retrospectively analyzed, and divided into robot group and control group. Intraoperative blood loss, surgical time, fluoroscopy frequency, total drilling times, infection rate, hospitalization time, and sacral fracture healing time were reviewed. Radiographs and computed tomography (CT) scans were totally acquired to evaluate the reduction quality, residual fracture displacement, and Gras classification on screws insertion after surgery. According to the Majeed scoring system, functional outcome was assessed for each patient at the final follow-up.

**Results:** There were 12 patients in the robot group and 20 patients in the control group with no significant difference about the demographic data. The average surgical time was 148.3 ± 40.5 min with intraoperative blood loss of 142.5±36.7 mL in the robot group and 185.0 ± 47.8 min with 612.5 ± 182.7 mL in the control group ($P = 0.034$, $P = 0.000$). The robot group had a shorter mean hospitalization time at 19.9 ± 7.0 days compared to the control group with 28.6 ± 5.4 days ($P = 0.010$). The fluoroscopy frequency was 35.4 ± 3.0 in the robot group and 45.5 ± 3.6 in the control group ($P = 0.000$) and total drilling times were 7.1 ± 1.1 and 9.6 ± 1.3 ($P = 0.000$), respectively. The infection rate was 0% (0/12) in the robot group and 15% (3/20) in the control group ($P = 0.159$). According to the Gras classification on screw positioning, there were 11 cases in Grade I and 1 case in Grade II in the robot group, and 14 cases in Grade I and 6 cases in Grade II in the control group. All the patients were followed up consecutively for at least 12 months, with an average follow-up period of 17.1 ± 3.6 months. All sacral fractures healed with an average time of 3.8 ± 0.6 months in the robot group and 4.7 ± 0.7 months in the control group ($P = 0.000$). According to Majeed functional assessment investigation, the mean score of the patients was 87.2 ± 4.0 in the robot group and 83.1 ± 4.5 in the control group ($P = 0.015$).

**Conclusions:** Robot-aided minimally invasive lumbopelvic fixation for traumatic spinopelvic dissociation is a safe and feasible option with advantages of less intraoperative blood loss, less radiation damage, less hospitalization time, and better functional outcome.

**Key words:** Fracture Fixation; Internal; Minimally invasive surgical procedures; Pelvis; Robotics; Sacrum

Traumatic spinopelvic dissociation frequently occurs in high energy trauma after falling from a height, which belongs 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

**Address for correspondence** Jian Jia, MD, Department of Orthopaedics, Tianjin Hospital, 406 Jiefangnan Road, Tianjin, China 300211 Tel: 0086-022-60910256; Fax: 0086-022-60910259; Email: hospitaljj@163.com
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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 $S_1$ to $S_2$ 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 need to be treated because of the extreme instability of the posterior pelvic ring.

The purpose of surgical fixation is reconstruction of the lumbopelvic area to avoid malunion and allow early weight-bearing. The transiliac plate[2, 3], sacroiliac screws[4, 5], and transiliac rods fixation[6, 7] can be optimal options for posterior pelvic ring injuries. However, all of above 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 $S_1$ cannulated screws, lumbopelvic fixation can better maintain the rotational 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 orthopaedics, 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 for the treatment of orthopaedic patients. Some of the studies[10, 11] have shown positive results about the technique of free hand insertion with the sacroiliac screw or vertebra pedicle screw, which is simple and well-worth being popularized. However, surgeons will take a lot of time to complete the learning curve and become acquainted with the key techniques. In addition, excessive radiation exposure to patients and medical staff can cause great harm to their bodies. Compared with the non-navigation surgery, orthopaedic surgery under navigation guidance, especially with robot-aided technology, shows significantly better accuracy on screw positioning and less radiation damage[12–14].

The third generation of the Chinese-manufactured orthopaedic robot, TiRobot system, has been applied in our institution. The robotic system can assist surgeons to plan the trajectory, position and length of screw insertion by importing intraoperative C-arm images, so as to ensure that minimally invasive screw placement is more accurate, efficient, and safe. However, the application of robot-aided technology in minimally invasive treatment of traumatic spinopelvic dissociation has not been reported. Since March 2016, a total of 12 patients with traumatic spinopelvic dissociation underwent minimally invasive lumbopelvic fixation, and satisfactory clinical results were achieved compared with the conventional manual method. The purposes of this study were: (i) to summarize the fixation methods of traumatic spinopelvic dissociation; (ii) to report our close reduction technique and experience of minimally invasive lumbopelvic fixation; and (iii) to evaluate the clinical and radiological results with robot-aided surgery for traumatic spinopelvic dissociation.

## Methods

### *Inclusion and Exclusion Criteria*

We reviewed all patients with traumatic spinopelvic dissociation treated in our department from March 2010 to May 2019 and identified 40 patients. Inclusion criteria were: (i) traumatic spinopelvic dissociation of which duration from trauma to surgery was less than 4 weeks; (ii) patients treated with minimally invasive lumbopelvic fixation under robotic guidance; (iii) evaluation with imaging standard of Mears and Velyvis[15], positioning of screws of modified Gras classification[16], and function outcomes of Majeed scoring system[17]; (iv) comparison with patients treated with conventional open reduction and lumbopelvic fixation; and (v) retrospective study.

Exclusion criteria were: (i) patients with severe thoracic or craniocerebral trauma who could not tolerate a prone position; (ii) type I sacral fracture in Roy-Camille classification; (iii) premature fractures; and (iv) pathological fractures.

Eight patients were excluded because of the exclusion criteria. Among these cases, seven cases were treated with sacral osteotomy because the duration from trauma to surgery was more than 4 weeks and one case had to be treated conservatively because of severe craniocerebral trauma. Therefore, 32 patients were enrolled in this study. This retrospective study protocol was approved by the medical ethics committee in our institution, and written informed consent was obtained from all participants included in the study.

The patients with unstable hemodynamics were treated with blood volume expansion therapy after admission. Bifemoral supracondylar skeletal tractions were performed to correct vertical displacement of the sacral fractures. Once the patients were medically stable, preoperative three-dimensional computed tomography (CT) scans and magnetic resonance of sacral nerves (MRN) were completed, which were essential for surgeons to make surgical planning of both the fractures and the sacral nerves.

According to the different surgical method, 32 patients were divided into robot-aided minimally invasive lumbopelvic fixation group (robot group) and conventional open reduction and lumbopelvic fixation group (control group). There were eight males and four females in the robot group, and the ages ranged from 13 to 60 years. The mechanisms of injury were falling or jumping from a height in 10 cases and traffic accident in two cases. All sacral fractures were type III according to Denis classification[18]. Depending on the fracture configuration, nine sacral fractures were "U-shaped," two was "H-shaped," and one was "Y-shaped." According to Roy-Camille classification[1], six sacral fractures were classified as type II, four as type III, and two as type IV. Nine patients were associated with anterior pelvic ring injuries, which included disruption of the symphysis pubis in one case, pubic ramus fractures in seven cases, and ipsilateral acetabular fracture in one case. Eight patients had sacral nerve injuries due to sacral fractures with grade III of Gibbons classification[19] in three patients and grade II in five patients. There were 13 males and seven females in the control group, and the age of these patients ranged from 15 to 62 years. The mechanisms of injury were falling or jumping from height in 15 cases and traffic accident in five cases. All sacral fractures were type III according to Denis classification[18]. Depending on the fracture configuration, 16 sacral fractures were "U-shaped," three was "H-shaped," and one was "Y-shaped." Nine sacral fractures were classified as type II, six cases as type III, and five cases as type IV according to Roy-Camille classification[1]. Fifteen patients were associated with anterior pelvic ring injuries, which included disruption of the symphysis pubis in two cases, pubic ramus fractures in 11 cases, and ipsilateral acetabular fracture in two cases. Fourteen patients had nerve injuries due to sacral fractures. The Gibbons classification[19] was grade IV in two patients, grade III in five patients, and grade II in seven patients.

The timing of surgical treatment, operation time and estimated blood loss were recorded. Immediate radiographs and CT scans were reviewed to evaluate the reduction quality and hardware position.

### *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 is a C-arm X-ray and CT machine (Siemens, Germany), φ6.5-mm cannulated screw, φ7-mm polyaxial iliac screw and φ6-mm polyaxial pedicle screw systems (Kanghui Medical Instruments, China).

### *Surgical Procedures*

All procedures were performed by a group of orthopaedic surgeons with rich experience.

The patients were administered general anesthesia with tracheal intubation after being placed in 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 min 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 $L_3$ spinous process percutaneously. After $L_5$ 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 $L_5$ vertebra anatomic feature, length, angulation, and direction of bilateral pedicle screws were designed and the simulation of the screw placement was completed on the images. 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 guidance of the preplanned trajectory outside the patient. 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. 1). Furthermore, a cannulated polyaxial pedicle screw of 6-mm diameter was inserted along the pin. Finally, the screw on the other side was inserted in the same way.

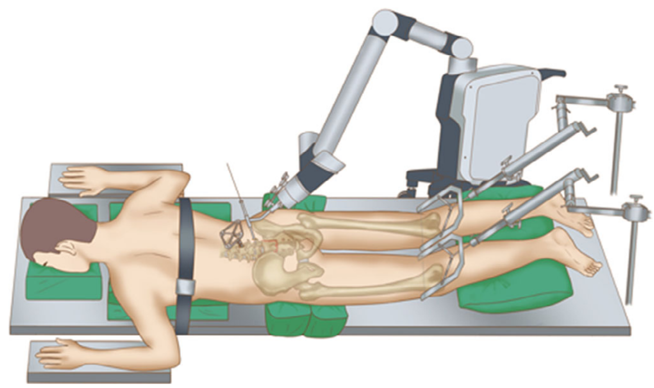

**Fig. 1** The patient is placed in the prone position on a radiolucent table. A navigation tracker is fixed on $L_3$ spinous process percutaneously. A guide pin is drilled into $L_5$ pedicle percutaneously under robotic guidance.

After the pedicle screws fixation, the bilateral posterior superior iliac spines (PSIS) were exposed subperiosteally through 3-cm incisions. We resected part of PSIS to avoid skin irritation caused by protruding screws and inserted a polyaxial iliac screw of 7-mm diameter and 10-cm length on each side. Meanwhile, we made 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 of 6.5-mm diameter were inserted subfascially and connected to the pedicle screw and iliac screw.

For the patients whose sacral nerves need to be decompressed, we performed a sacral laminectomy *via* a small isolated midline incision to remove the fragments that compressed the sacral nerves and release them before reducing sacral fractures. Then a Schantz pin can be screwed from PSIS into the iliac wing and rotated to reduce rotational displacement of the pelvic ring. Bifemoral skeletal traction was applied with countertraction through armpit fixation, provided there was no shoulder joint fracture. Once the bilateral vertical and rotational displacements were corrected with the distraction of the lumbopelvic devices such as reduction clamps, all connectors were fixed rigidly (Fig. 2). After the

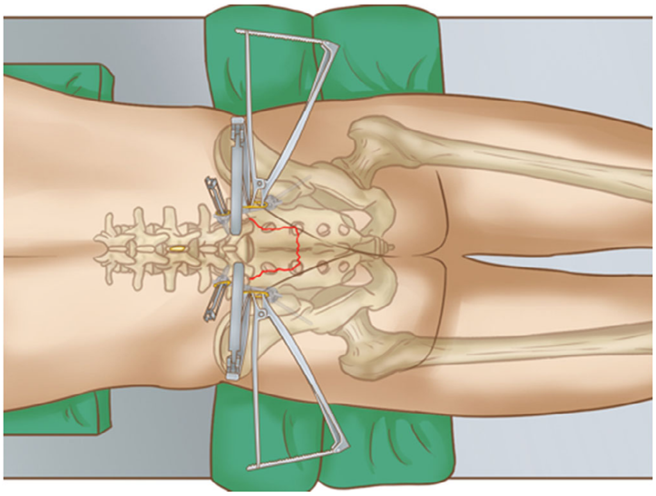

**Fig. 2** The bilateral vertical and rotational displacements are corrected with the distraction of the lumbopelvic devices.

reduction quality of the posterior pelvic ring fracture had been manifested satisfactorily with C-arm fluoroscopy, the skin and subcutaneous tissues were sutured. Finally, the bilateral $S_1$ sacroiliac screws were performed under robotic guidance if $S_1$ vestibule was big enough to pass through a cannulated screw with the diameter of 6.5 mm.

As for the cases in the control group, the conventional open reduction and lumbopelvic fixation associated were performed *via* a posterior midline incision.

***Postoperative Management***

All patients underwent the same management with intravenously administered antibiotics postoperatively continued for 24 h. 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 started usually at 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.

***Imaging Standard of Mears and Velyvis***

Maximum residual displacement in various directions were recorded and graded according to the imaging standard of Mears and Velyvis[15]. 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°).

***Screws Positioning of Modified Gras Classification***

A modified Gras classification was applied to assess the positioning of pedicle and sacroiliac screws under CT visualization[16]. 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.

***Function Outcomes of Majeed Scoring System***

The function outcomes were evaluated based upon the Majeed scoring system[17], 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 the patient was able to get out of bed. Patients began weight bearing 6 weeks after surgery.

***Statistical Analysis***

All data was processed by using SPSS20.0 statistical software (SPSS Inc., Chicago, IL, USA). Quantitative data were expressed as mean ± standard deviation (SD) and were compared using the Student *t*-test. Categoric variables were compared using the Pearson $X^2$ test. The *P*-value was set <0.05 for significance.

## Results

***Patients' Information***

There were similarities in gender, age, BMI, injury mechanism, sacral nerve injuries, and preoperative time, with no statistical significance in patient characteristics between the two groups (Table 1).

All traumatic spinopelvic dissociation of the patients in the two groups were reduced and stabilized with lumbopelvic fixation. Bilateral sacroiliac screws (1-1 SI screws in each case) were performed in 24 patients, which included nine cases and 15 cases in the robot group and the control group, respectively. Open reduction and internal fixation were performed with three acetabular fractures, which included one case in the robot group and two cases in the control group. Three cases of disruption of the symphysis pubis were fixed with plates simultaneously. As for the fractures of pubic ramus with significant displacement, minimally invasive open reduction and cannulated screw or plate fixation were performed under robotic guidance.

The result of patients with perioperative clinical indicators in the two groups were compared (Table 2). The average surgical time in the robot group was 148.3 ± 40.5 min (range, 95–220 min), with intraoperative blood loss of 142.5 ± 36.7 mL (range, 90–250 mL). Whereas, the average surgical time (incision to closure) in the control group was 185.0 ± 47.8 min (range, 150–240 min), with intraoperative blood loss of 612.5 ± 182.7 mL (range, 180-1250 mL) much higher than values in the robot group. The robot group had

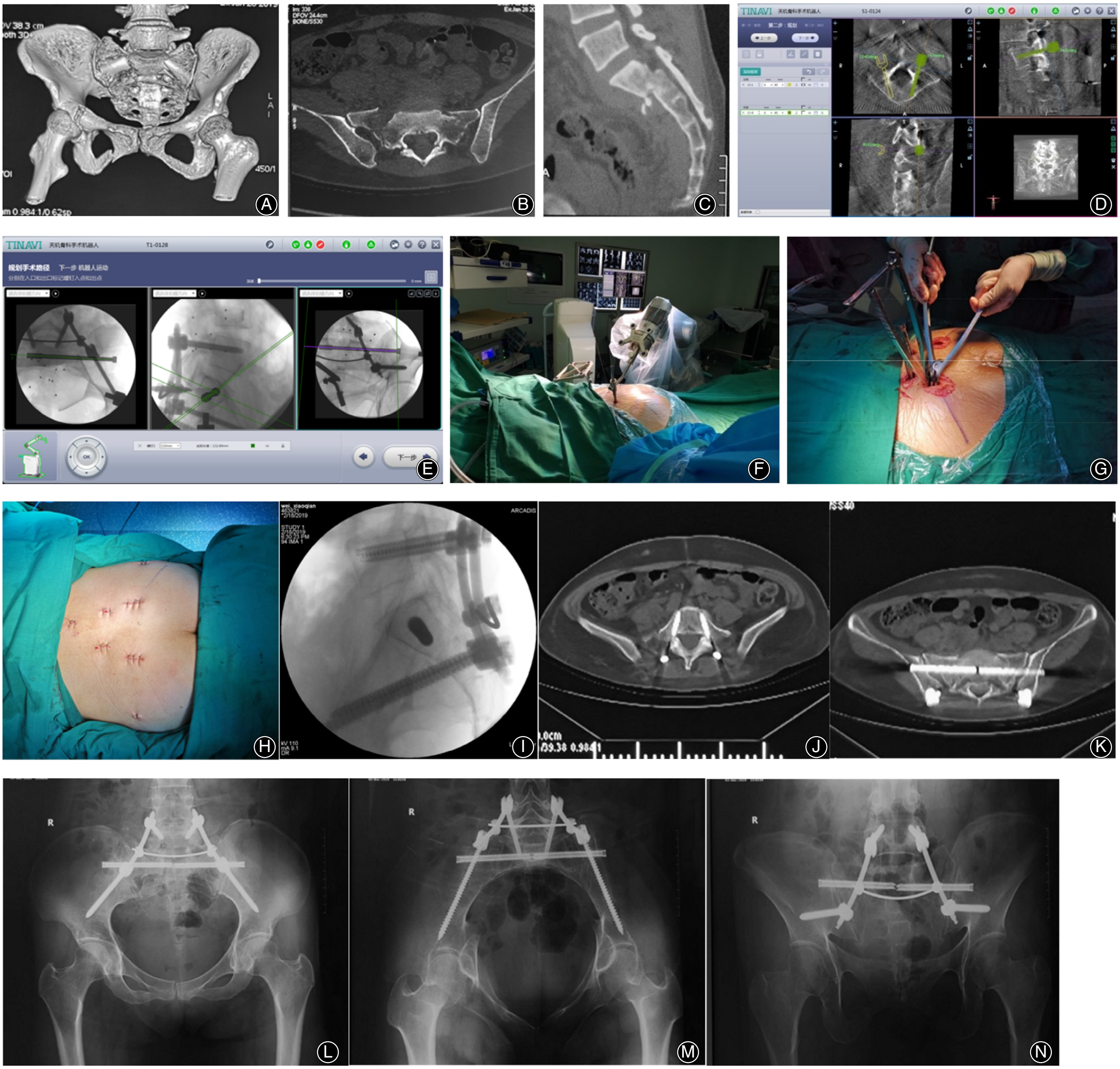

**Fig. 3** Female, 37-year-old, falling from height, a U-shaped sacral fracture associated with pubic rami fractures, treated with minimally invasive lumbopelvic fixation and percutaneous sacroiliac screws fixation of sacral fracture under robotic guidance. (A) CT reconstruction image; (B) Axial CT view; (C) Sagittal CT view; (D) Robot-aided path planning of bilateral pedicle screws placement in $L_5$; (E) Robot-aided path planning of bilateral sacroiliac screws placement in $S_1$; (F) The guide pin insertion in $L_5$ pedicle following the guidance of the robotic arm; (G) Reduction with a distraction clamp to correct the vertical displacement of the sacral fracture after the screws and rods were inserted percutaneously; (H) The length of each incision was less than 3 cm, and they were placed symmetrically because of bilateral fixation with the same method; (I) Intraoperative lateral view; (J) Postoperative axial CT view of $L_5$ showing appropriate insertion of bilateral $L_5$ pedicle screws; (K) Postoperative axial CT view of $S_1$ showing appropriate insertion of bilateral $S_1$ sacroiliac screws; (L) Postoperative anteroposterior view; (M) Postoperative inlet view; (N) Postoperative outlet view.

a shorter average hospitalization time at 19.9 ± 7.0 days compared to the control group with 28.6 ± 5.4 days ($P = 0.010$).

All the patients were followed up consecutively for at least 12 months, with an average follow-up period of 17.1 ± 3.6 months. Secondary loss of reduction or hardware

**TABLE 1 Patient characteristics of the two groups**

| Patient characteristics | Robot group (*n* = 12) | Control group (*n* = 20) | $t/\chi^2$ | *P* value |
|---|---|---|---|---|
| Age(year), Mean ± SD | 35.25 ± 11.69 | 37.65 ± 10.72 | −0.346 | 0.732 |
| Gender, *n*(%) | | | 0.009 | 0.923 |
| Male | 8(66.7) | 13(65) | | |
| Female | 4(33.3) | 7(35) | | |
| BMI (kg/m$^2$), Mean ± SD | 25.7 ± 3.6 | 25.0 ± 3.3 | 0.530 | 0.600 |
| Injury mechanism, *n*(%) | | | 0.305 | 0.581 |
| Falling or jumping | 10(83.3) | 15(75) | | |
| Traffic accident | 2(16.7) | 5(25) | | |
| Sacral nerve injuries, *n*(%) | | | 0.039 | 0.844 |
| Yes | 8(66.7) | 14(70) | | |
| No | 4(33.3) | 6(30) | | |
| Preoperative time(days), Mean ± SD | 10.58 ± 7.0 | 12.35 ± 5.4 | −0.804 | 0.428 |

BMI, body mass index; Mean ± SD, mean ± standard deviation; *n*, patient number; t, Independent t-test; $\chi^2$, Chi-square test.

**TABLE 2 The result of patients in the two groups of patients with perioperative clinical indicators**

| Results | Robot group | Control group | $t/\chi^2$ | *P* value |
|---|---|---|---|---|
| Intraoperative blood loss (mL), Mean ± SD | 142.5 ± 36.7 | 612.5 ± 182.7 | −8.750 | <0.001 |
| Surgical time(min), Mean ± SD | 148.3 ± 40.5 | 185.0 ± 47.8 | −2.218 | 0.034 |
| Fluoroscopy frequency, Mean ± SD | 35.4 ± 3.0 | 45.5 ± 3.6 | −8.180 | <0.001 |
| Total drilling times, Mean ± SD | 7.1 ± 1.1 | 9.6 ± 1.3 | −5.709 | <0.001 |
| Residual displacement (mm) | 1.73 ± 0.31 | 1.58 ± 0.28 | −1.385 | 0.176 |
| Infection rate, *n*(%) | 0% (0/12) | 15% (3/20) | 1.986 | 0.159 |
| Hospitalization time(day), Mean ± SD | 19.9 ± 7.0 | 28.6 ± 5.4 | −3.810 | 0.010 |
| Gras classification evaluation, *n*(%) | | | 2.060 | 0.151 |
| Grade I | 11(91.7) | 14(70) | | |
| Grade II | 1(8.3) | 6(30) | | |
| Sacral fracture healing time(months), Mean ± SD | 3.8 ± 0.6 | 4.7 ± 0.7 | −4.152 | <0.001 |
| Majeed score, Mean ± SD | 87.2 ± 4.0 | 83.1 ± 4.5 | 2.574 | 0.015 |

M ± SD, mean ± standard deviation; n, patient number; t, Independent t-test; $\chi^2$, Chi-square test.

failure did not occur in both groups during the follow-ups. The sacral fractures healed with an average time of 3.8 ± 0.6 months in the robot group and 4.7 ± 0.7 months in the control group with significant difference ($P < 0.001$). A total of 28 patients underwent hardware removal between 12 months and 24 months after surgery, despite having offered to remove implants for all patients. Because of no pain caused by the implants, the other four patients did not have their implants removed.

There were three patients with sacral nerve injury of grade III in the robot group and seven patients with sacral nerve injury of grade III or IV in the control group who underwent decompression. At the final follow-ups, in three patients in the robot group who underwent nerve decompression, two patients were improved from grade III to I and one patient from grade III to II with residual neurological symptoms. In seven patients in the control group who underwent nerve decompression, three patients were improved from grade III to I, two patients from grade III to II, one patient from IV to II, and one patient from grade IV to III with residual neurological symptoms. In five patients with Gibbons grade II without decompression in the robot group, four patients with sacral nerve injury were improved to grade I and one patient maintained grade II. Similarly, in seven patients with Gibbons grade II without decompression in the control group, six patients with sacral nerve injury were improved to grade I and one patient maintained grade II.

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.

### *Screws Positioning of Modified Gras Classification*

Postoperative X-ray images and CT scans showed that all the pelvic rings were in good shape and there was no incidence of screw perforation. According to modified Gras classification on screw positioning[16], there were Grade I in 11 cases and Grade II in one case (left $S_1$ screw) in the robot group.

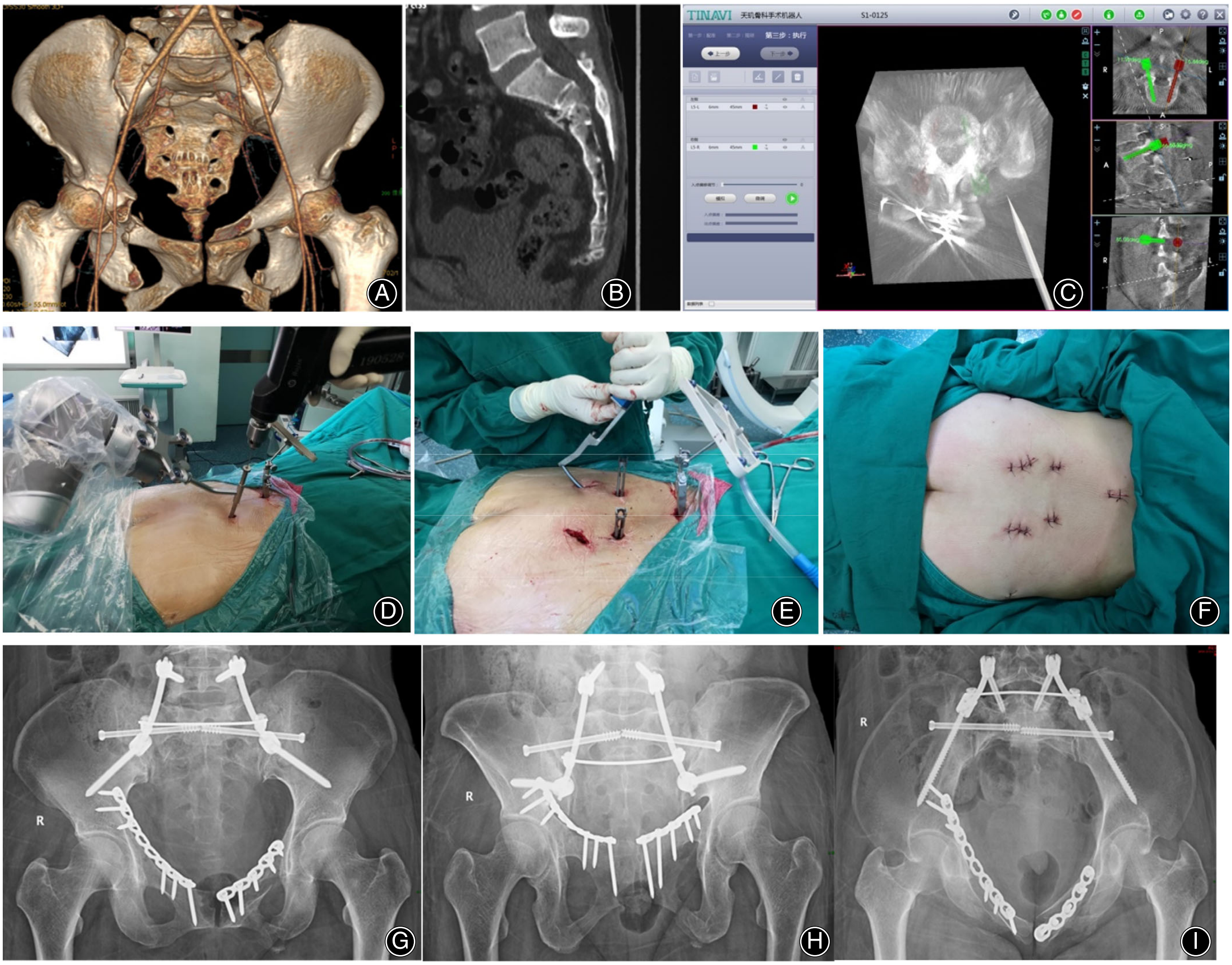

**Fig. 4** Female, 54-year-old, traffic accident injury, a U-shaped sacral fracture associated with bilateral pubic rami fractures, treated with open reduction and plate osteosynthesis of pubic rami fractures and minimally invasive lumbopelvic fixation and percutaneous sacroiliac screws fixation of sacral fracture under robotic guidance. (A) Preoperative CT 3D reconstruction of pelvis; (B) Sagittal CT scan of the sacrum; (C) Robot-aided path planning after C-arm radiograph collection; (D) Robot-aided guide pin insertion of $L_5$ pedicle; (E) Percutaneous rod insertion; (F) intraoperative incisions; (G) Postoperative anteroposterior view; (H) Postoperative outlet view; (I) Postoperative inlet view.

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 deviation and the angular deviation were 2.12 ± 1.03 mm and 4.15° ± 1.74°, respectively.

### *Imaging Standard of Mears and Velyvis*

According to the imaging standards given by Mears and Velyvis[15], the radiological results evaluated with postoperative radiographs and CT scans showed that there were eight cases with anatomical reduction and four cases with satisfactory reduction in the robot group. The residual displacements of the robot group and the control group were 1.73 ± 0.31 mm and 1.58 ± 0.28 mm, respectively ($P = 0.176$).

### *Function Outcomes of Majeed Scoring System*

All patients in the two groups completed the Majeed[17] functional assessment investigation at their final follow-ups. The score was 87.2 ± 4.0 in the robot group, which were graded as follows: 8, excellent and 4, good. Compared with the robot group, the scores of patients in the control group was 83.1 ± 4.5, which were graded as follows: 13 as excellent, 5 as good, and 2 as fair. There was significant difference ($P = 0.015$).

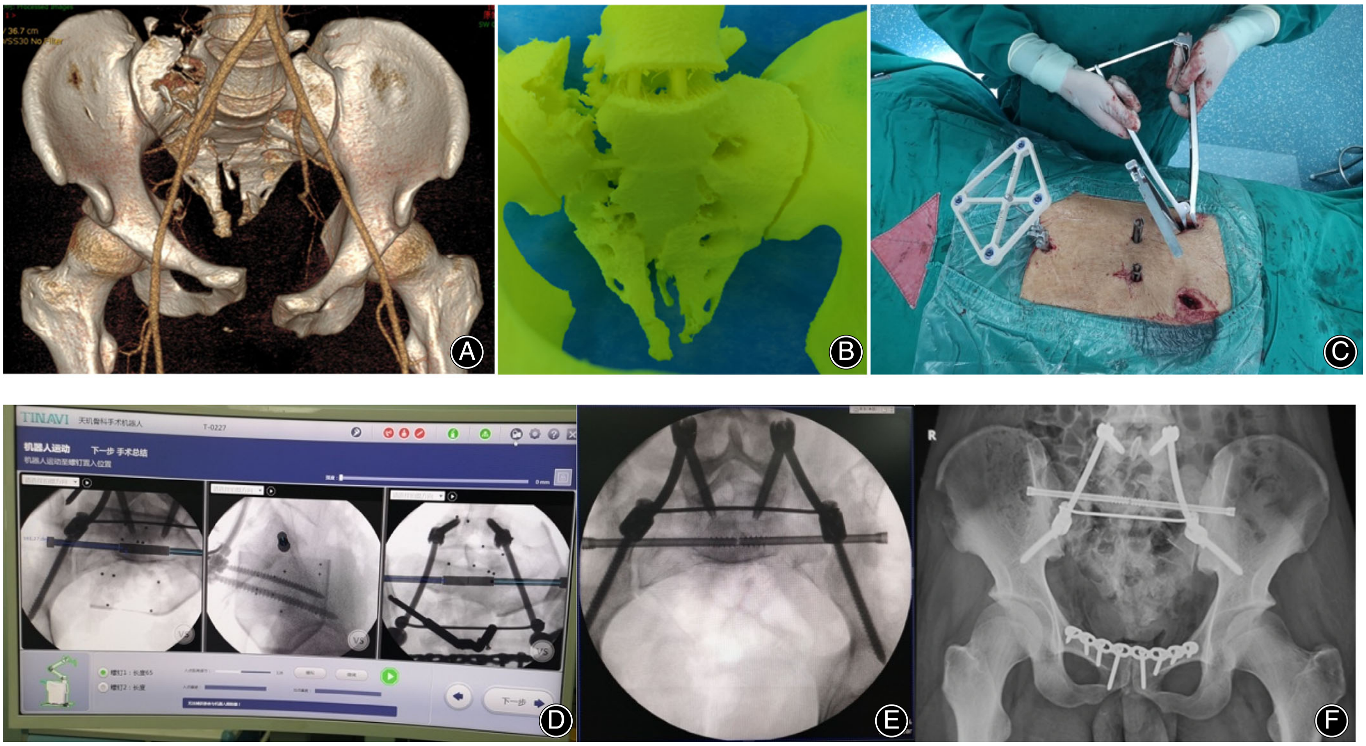

**Fig. 5** Male, 22-year-old, falling from height, a Y-shaped sacral fracture associated with disruption of pubic symphysis, treated with open reduction and plate osteosynthesis of pubic symphysis, minimally invasive lumbopelvic fixation, and percutaneous sacroiliac screws fixation of sacral fracture under robotic guidance. (A) Preoperative CT 3D reconstruction; (B) 3D printing model; (C) Robot-aided path planning after C-arm radiograph collection; (D) Robot-aided path planning after C-arm radiograph collection; (E) Intraoperative image; (F) Postoperative anteroposterior radiograph.

### *Complications*

No patient suffered a neurovascular injury intraoperatively. No incision infection, fat necrosis, or other incision-related complications occurred postoperatively in the robot group. There were three patients who had wound infection in the control group. One of them had superficial infection secondary to fat liquefaction 2 weeks after surgery, and the other patients had deep infection 1 week after surgery. After thorough debridement and sensitive antibiotic treatment, the infections were under control and the incisions healed successfully 3 weeks later. Five patients (two patients in robot group and three patients in control group) made complaints about irritation because of prominent implants, although we resected part of the PSIS to ensure the screw taps were lower than bone surface.

Typical cases were shown in Figs. 3-5.

## Discussion

### *Fixation Methods of Traumatic Spinopelvic Dissociation*

Traumatic spinopelvic dissociation essentially separates the lower lumbar spine from the pelvis, which usually occurs 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[20]. 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[21] 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[22]. The technique could provide enough distraction to reduce and fix vertical shear fracture of bilateral sacrum, but it does not 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 transiliac plate firstly described by Shildhauer[23], 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 are used to treating bilateral sacral fractures with lumbopelvic fixation using with S1 sacroiliac screws unless the bone tunnel is too narrow or there is a transverse fracture line in S1 vertebra[8]. Therefore, the fixation strength for spinopelvic dissociation is enough to maintain the reduction and enable early weight bearing.

### *Clinical and Radiological Results with Robot-Aided Surgery*

Although the lumbopelvic fixation with open surgery can provide enough rigidity, the rate of wound-healing disturbances, which are as high as 26%, is still a big problem due to invasive procedure[24]. 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, and especially reducing infection rate have been repeatedly reported[9, 10, 12, 25]. Koshimune[26] compared conventional open lumbopelvic fixation with minimally invasive procedure for unstable bilateral sacral fractures. Infection occurred in three of eight cases with the conventional method, and in none of the eight patients with the minimally invasive method. In our series, none of the 12 patients in the robot group had wound-related complications and the infection rate was 15% (3/20) in the control group. However, there is no statistical difference in the results ($P$ = 0.159). In our opinion, the main reason is the small number of cases in the two groups. After all, the damage of soft tissue caused by minimally invasive surgery is significantly less than that with conventional operation procedure. This can be explained by the fact that we did not detach the paraspinal muscles because the pedicle screws were inserted percutaneously during the procedure. Furthermore, the close reduction was performed under C-arm fluoroscopy with distraction clamps as well as countertraction of the patient. Two patients in robot group and three patients in control group made complaints of skin pain around PSIS, which is one of the common problems after lumbopelvic fixation. The part of the PSIS was resected to ensure the screw taps inserted into the bone as much as possible especially in the thin patients. In fact, screws that did not initially protrude at the time of surgery may became more prominent after weight loss of the patients.

Excessive drilling does affect the holding force of screws, thus reducing the stability of implants and increasing the failure risk. Hou provided the idea that the application of the axial projection of the S1 pedicle could be effective during the produce of sacroiliac screw insertion[11]. However, as for the sacral fracture in lumbopelvic dissociation, it's difficult to find the intact symbol because of the comminuted fragments around the channel.

Using 3D fluoroscopic navigation when performing pelvic surgery is reported to be useful in planning 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% to 31%, demonstrating that there's still certain room to improve the technology[27–29]. Additionally, too much radiation exposure to patients and surgeons will also cause great harm to their bodies.

### *Close Reduction Technique and Experience of Minimally Invasive Lumbopelvic Fixation*

In recent years, the emergence of surgical robots provided surgeons with an innovative technology which has revolutionary impacts on intraoperative guidance. Some existing studies and reported cases summarized that the accuracy of screw placement with robot-assisted technique was superior to the conventional free-hand technique[30, 31]. Under robotic guidance, it is safe and effective to achieve the correct trajectory of pelvic screw with over 95% accuracy[32]. 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 orthopaedic surgery robot system developed independently in China and recognized internationally. From 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 end. The postoperative CT scans revealed that there was no screw perforation in all eight 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[33]. 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 occurring in extremities[34, 35].

In patients who are associated with sacral nerve injuries, we agree with the relatively consistent points on decompression[9]. We do not perform a sacral laminectomy for the patients whose perineal sensation and rectal tone are intact, unless the nerve roots are compressed by obvious "key fragments" shown on CT scans or MRN. We strived to achieve an indirect reduction for the most patients in the two groups. The results are relatively satisfactory, except for one patient with Gibbons classification of grade IV in whom most of their sacral nerves were disrupted because of the severe injury.

## Conclusion

Robot-aided minimally invasive lumbopelvic fixation for traumatic spinopelvic dissociation has the advantages with less bleeding, less damage, quick recovery, and more accuracy, making it a safe and effective surgical technique. The clinical results of minimally invasive lumbopelvic fixation under robot guidance is much better than conventional open procedure for traumatic spinopelvic dissociation. In patients whose durations from injury to operation are more than 4 weeks, the number and strength of spinopelvic fixation should be enhanced and open procedure for anatomical reduction probably need to be done. However, accumulation of cases is warranted to provide the necessary evidence to guide clinical practice.

## References


**1.** Roy-Camille R, Saillant G, Gagna G, Mazel C. Transverse fracture of the upper sacrum. Suicidal jumper's fracture. Spine (Phila Pa 1976), 1985, 10: 838–845.
**2.** Krappinger D, Larndorfer R, Struve P, Rosenberger R, Arora R, Blauth M. Minimally invasive transiliac plate osteosynthesis for type C injuries of the pelvic ring: a clinical and radiological follow-up. J Orthop Trauma, 2007, 21: 595–602.
**3.** Kobbe P, Hockertz I, Sellei RM, Reilmann H, Hockertz T. Minimally invasive stabilisation of posterior pelvic-ring instabilities with a transiliac locked compression plate. Int Orthop, 2012, 36: 159–164.
**4.** Iorio JA, Jakoi AM, Rehman S. Percutaneous sacroiliac screw fixation of the posterior pelvic ring. Orthop Clin North Am, 2015, 46: 511–521.
**5.** Tidwell J, Cho R, Reid JS, Boateng H, Copeland C, Sirlin E. Percutaneous sacroiliac screw technique. J Orthop Trauma, 2016, 30: S19–S20.
**6.** Wang H, Fu YH, Ke C, *et al*. Minimally invasive stabilisation of posterior pelvic ring instabilities with pedicle screws connected to a transverse rod. Int Orthop, 2018, 42: 681–686.
**7.** Hua X, Yan SG, Cui Y, Yin Z, Schreiner AJ, Schmidutz F. Minimally invasive internal fixator for unstable pelvic ring injuries with a pedicle screw-rod system: a retrospective study of 23 patients after 13.5 months. Arch Orthop Trauma Surg, 2019, 139: 489–496.
**8.** Tian W, Chen WH, Jia J. Traumatic Spino-pelvic dissociation with bilateral triangular fixation. Orthop Surg, 2018, 10: 205–211.
**9.** Williams SK, Quinnan SM. Percutaneous lumbopelvic fixation for reduction and stabilization of sacral fractures with spinopelvic dissociation patterns. J Orthop Trauma, 2016, 30: e318–e324.
**10.** Kanezaki S, Miyazaki M, Notani N, *et al*. Minimally invasive triangular osteosynthesis for highly unstable sacral fractures: technical notes and preliminary clinical outcomes. Medicine (Baltimore), 2019, 98: e16004.
**11.** Hou Z, Zhang Q, Chen W, *et al*. The application of the axial view projection of the S1 pedicel for sacroiliac screw. J Trauma, 2010, 69: 122–127.
**12.** Zheng G, Nolte LP. Computer-assisted orthopedic surgery: current state and future perspective. Front Surg, 2015, 23: 2–66.
**13.** Liu HS, Duan SJ, Xin FZ, Zhang Z, Wang XG, Liu SD. Robot-assisted minimally-invasive internal fixation of pelvic ring injuries: a single-center experience. Orthop Surg, 2019, 11: 42–51.
**14.** Wu XB, Wang JQ, Sun X, Han W. Guidance for the treatment of femoral neck fracture with precise minimally invasive internal fixation based on the orthopaedic surgery robot positioning system. Orthop Surg, 2019, 11: 335–340.
**15.** Mears DC, Velyvis J. Surgical reconstruction of late pelvic post-traumatic nonunion and malalignment. J Bone Joint Surg Br, 2003, 85: 21–30.
**16.** Gras F, Marintschev I, Wilharm A, Klos K, Mückley T, Hofmann GO. 2D-fluoroscopic navigated percutaneous screw fixation of pelvic ring injuries–a case series. BMC Musculoskelet Disord, 2010, 11: 153.
**17.** Majeed SA. Grading the outcome of pelvic fractures. J Bone Joint Surg Br, 1989, 71: 304–306.
**18.** Denis F, Davis S, Comfort T. Sacral fractures: an important problem. Retrospective analysis of 236 cases. Clin Orthop Relat Res, 1988, 227: 67–81.
**19.** Gibbons KJ, Soloniuk DS, Razack N. Neurological injury and patterns of sacral fractures. J Neurosurg, 1990, 72: 889–893.
**20.** DeRogatis MJ, Breceda AP, Lee P, Issack PS. Sacral fractures with spondylopelvic dissociation. JBJS Rev, 2018, 6: e3.
**21.** Nork SE, Jones CB, Harding SP, Mirza SK, Routt ML Jr. Percutaneous stabilization of U-shaped sacral fractures using iliosacral screws: technique and early results. J Orthop Trauma, 2001, 15: 238–246.
**22.** Piltz S, Rubenbauer B, Böcker W, Trentzsch H. Reduction and fixation of displaced U-shaped sacral fractures using lumbopelvic fixation: technical recommendations. Eur Spine J, 2018, 27: 3025–3033.
**23.** Schildhauer TA, Ledoux WR, Chapman JR, Henley MB, Tencer AF, Routt ML Jr. Triangular osteosynthesis and iliosacral screw fixation for unstable sacral fractures: a cadaveric and biomechanical evaluation under cyclic loads. J Orthop Trauma, 2003, 17: 22–31.
**24.** Bellabarba C, Schildhauer TA, Vaccaro AR, Chapman JR. Complications associated with surgical stabilization of high-grade sacral fracture dislocations with spino-pelvic instability. Spine (Phila Pa 1976), 2006, 15: S80–S88.
**25.** Spalteholz M, Gulow J. 3D image enhancer-adjusted percutaneous triangular stabilization of geriatric pelvic ring fractures: operation technique and indications. Unfallchirurg, 2019, 122: 880–884.
**26.** Koshimune K, Ito Y, Sugimoto Y, *et al*. Minimally invasive spinopelvic fixation for unstable bilateral sacral fractures. Clin Spine Surg, 2016, 29: 124–127.
**27.** Pieske O, Landersdorfer C, Trumm C, *et al*. CT-guided sacroiliac percutaneous screw placement in unstable posterior pelvic ring injuries: accuracy of screw position, injury reduction and complications in 71 patients with 136 screws. Injury, 2015, 46: 333–339.
**28.** Ghisla S, Napoli F, Lehoczky G, *et al*. Posterior pelvic ring fractures: intraoperative 3D-CT guided navigation for accurate positioning of sacro-iliac screws. Orthop Traumatol Surg Res, 2018, 104: 1063–1067.
**29.** Takao M, Hamada H, Sakai T, Sugano N. Clinical application of navigation in the surgical treatment of a pelvic ring injury and acetabular fracture. Adv Exp Med Biol, 2018, 1093: 289–305.
**30.** Hyun SJ, Kim KJ, Jahng TA. S2 alar iliac screw placement under robotic guidance for adult spinal deformity patients: technical note. Eur Spine J, 2017, 26: 2198–2203.
**31.** Liuzza F, Capasso L, Florio M, *et al*. Transiliosacral fixation using the O-ARM2® and STEALTHSTATION® navigation system. J Biol Regul Homeost Agents, 2018, 32: 163–171.
**32.** Laratta JL, Shillingford JN, Meredith JS, Lenke LG, Lehman RA, Gum JL. Robotic versus freehand S2 alar iliac fixation: in-depth technical considerations. J Spine Surg, 2018, 4: 638–644.
**33.** Takao M, Hamada H, Sakai T, Sugano N. Factors influencing the accuracy of iliosacral screw insertion using 3D fluoroscopic navigation. Arch Orthop Trauma Surg, 2019, 139: 189–195.
**34.** Dagnino G, Georgilas I, Morad S, *et al*. Image-guided surgical robotic system for percutaneous reduction of joint fractures. Ann Biomed Eng, 2017, 45: 2648–2662.
**35.** Kim WY, Ko SY. Hands-on robot-assisted fracture reduction system guided by a linear guidance constraints controller using a pre-operatively planned goal pose. Int J Med Robot, 2019, 15: e1967.