Comparative Study of Triangular Osteosynthesis with and without Robotic Assistance for Unilateral Unstable Sacral Fractures Involving Lumbosacral Junction Injuries

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Abstract

Background To compare the therapeutic effects of triangular osteosynthesis (TOS) with and without robotic assistance for unilateral unstable sacral fractures (USFs) involving lumbosacral junction injuries (LSJIs).

Methods

Patients with unilateral USF involving ipsilateral LSJI fixed with TOS were retrospectively analyzed and divided into two groups: the robot group (TOS with robotic assistance) and the conventional group (open reduction and TOS fixation). Screw position was assessed with Gras criterion. Patients were followed up with routine visits for clinical and radiographic examination. Clinical function outcome was recorded and scored with Majeed scoring system at last follow-up.

Results

Eleven patients in the robot group and seventeen patients in the conventional group were recruited into this study. Significant differences in surgical bleeding ($P < 0.001$) and fluoroscopy times ($P = 0.002$) were noted between the two groups. Operation time ($P = 0.027$) and fracture healing time ($P = 0.041$) was shorter in the robot group. There was no difference on postoperative residual displacement between the two groups ($P = 0.971$). According to the modified Gras criterion, the percentages of grade I on sacroiliac screws were 90.9% (10/11) and 70.6% (12/17), and that on pedicle screws were 100% (11/11) and 100% (17/17), respectively. The rate of incision-related complications was 0% (0/11) in the robot group and 11.8% (2/17) in the conventional group. Statistical difference was shown on the Majeed criterion ($P = 0.039$), with higher scores in the robot group.

Conclusion

TOS with robotic assistance for the treatment of USFs involving LSJIs was minimally invasive and feasible, with the advantages of decreasing fluoroscopy and incision-related complications.

Background

Unstable sacral fractures (USFs), including vertical and/or rotational instabilities, are usually caused by high-energy trauma, especially falls from height. As an USF involving the sacral foramina, fracture or dislocation of the ipsilateral L5/S1 facet process is probably occurred, which is mainly caused by the upward extension of the high transverse or longitudinal fracture line [1]. According to the description of lumbosacral junction injuries (LSJIs) initially from Isler [2], classification can be summarized as follows: type I (extraarticular lesions), type II (articular lesions) and type III (complex lesions). Of type II lesions, three subtypes were classified with IIa (fractures of the S1 facet), IIb (fractures medial to the S1 facet) and IIc (with rotation of the hemipelvis and subluxation of the S1 facet).

Significantly displaced USFs, especially associated with LSJIs, predictably lead to spinopelvic instabilities with potentially adverse functional consequences, including lumbosacral pain and gait changes. The treatment aims to reconstruct the sacral anatomy and achieve the sufficient stability in the spinopelvic area for early mobilization. In recent years, sacroiliac screw or bend plate fixation, aimed at the fixation between ilium and sacrum, is reliable for the reduced or un-displaced posterior pelvic ring injury, even sacral fractures with type I LSJIs [3, 4]. However, if severer LSJIs occurs in USFs, sacroiliac screw or posterior plate fixation is inappropriate due to the insufficient stability at the lumbosacral junction.

The unilateral spinopelvic fixation for vertically USFs, called as distraction spondylodesis, was first described by Kach and Trentz [5]. As a modification, triangle osteosynthesis has the devices by connecting the lumbar spine to the ilium and a supplemental sacroiliac screw, with the function of reducing sacral fractures. This construct can also indirectly stabilize the affected lumbosacral junction by crossing the spinopelvic area. Compared with the sacroiliac screw and the posterior plate, triangle osteosynthesis has significant advantages on biomechanics for the treatment of vertically USFs [6–9].

However, literatures reveal that complication rates associated with their implantation are not insignificant. Owing to the open reduction and soft tissue dissection, the reported deep infection rate was 8% and wound healing disturbance rate was as high as 26%, particularly in those patients with multi-planar sacral fractures requiring bilateral fixation [10–12]. In recent years, to overcome the shortcomings of conventional open surgery, minimally invasive orthopedic surgery aimed to bring benefits, such as less bleeding and early postoperative rehabilitation. It's still problematic to ensure that each screw is inserted accurately in the optimal area with free-hand technique under fluoroscopic guidance although percutaneous lumbopelvic fixation has been proved to be an effective surgical procedure for stabilizing USFs. The reported incidence of mal-positioned sacroiliac screws ranges from 2–15% [13, 14], and the incidence of neurological impairment ranges from 0.5–7.7% [13, 15], which still need deliberate consideration. Additionally, since bony landmarks at the surgical site used in the process of guide pin implantation often need to be visualized clearly with fluoroscopy, patients and surgeons are subject to large amounts of harmful radiation. Consequently, the desire for decreasing complication rates, avoiding excessive radiation and improving accuracy lead to the development of computer navigation and robot-assisted surgery [16, 17]. Although some studies on robot-assisted pelvic fracture fixation have already been reported, minimally invasive triangular osteosynthesis with robotic assistance for the treatment of USFs is still lacking.

To date, triangular osteosynthesis with and without robotic assistance have been performed in our constitution for patients with unilateral USFs involving ipsilateral LSJIs. The purposes of this study were to retrospectively analyze these data, compare therapeutic effects, and discuss existing problems with utilization of orthopedic surgery robots.

Methods

Patients

Inclusion criteria for this study were skeletally mature patients with the unilateral USFs involving ipsilateral LSJIs treated with robot-aided minimally invasive triangular osteosynthesis or conventional open reduction and triangular osteosynthesis fixation. Exclusion criteria were as follows: (1) the time from injury to surgery was more than 4 weeks; (2) patients whose S1 vestibula is too narrow to accommodate a cannulated screw with the diameter of 6.5mm, (3) the injured sacral nerves need to be decompressed, (4) the follow-up period was less than 12 months. Referring to inclusion and exclusion criteria, a total of 28 patients were analyzed retrospectively from March 2010 to January 2021.

All patients were divided into two groups: the robot group (minimally invasive triangular osteosynthesis with robotic assistance) and the conventional group (open reduction and triangular osteosynthesis fixation). The most common mechanism of injury was a fall from height (17 cases) and vehicle accidents (8 cases), with 3 cases caused by crushing injuries. All patients combined anterior pelvic ring injuries, including rami fractures in 22 patients, a symphyseal disruption alone in 4 patients and symphyseal disruption in combination with a ramus fracture in 2 patients. Five patients had neurologic impairment to some component of the sacral plexus, with grade II of Gibbons classification [18]. According to Tile classification on pelvic fractures [19], there were 5 patients with type B and 19 patients with type C.

Skeletal tractions were performed in patients with vertically USFs to reduce and resist cephalad migration of the hemipelvis. X-ray trauma series and three-dimensional (3D) computed tomography (CT) scans were routinely obtained. Vestibular anatomy of S1 was measured with CT scans to ensure if a cannulated screw with the diameter of 6.5mm can pass through. Surgical treatment was performed once the patient was stable both physiologically and hemodynamically.

Surgical Equipment

The TiRobot system (TINAVI Medical Technologies, Beijing, China) for orthopaedic surgery was made in China, containing a main console with a surgical planning and controlling workstation, an optical tracking system, and a robotic arm with six joints (Fig. 1). The C-arm machine was produced by Siemens (Germany). The pedicle screws, iliac screws, rods and cannulated screws were produced by Kanghui (China).

Surgical Methods

The surgical procedure of patients in the robot group

The patient was in prone position on a radiolucent operation table after general anesthesia. We established a sterile working environment for the robotic arm and assembled a locator at the end of the

six-joint-arm.

First, we fixed a spinal tracker on L3 spinous process through a 2-cm incision and moved the locator onto the skin at the surgical area (Fig. 2). After collecting the intraoperative fluoroscopy using a 3D C-arm machine, we transmitted the data into the TiRobot workstation. Next, planning the trajectory of L5 pedicle screw on the workstation (Fig. 3). We removed the locator at the end of the robotic arm and assembled a guider with a pilot sleeve, and then pressed the start button on the main console. The arm will arrive at the surgical area according to the command and automatically complete the screw positioning. Before inserting the guide pin, it is necessary to ensure that the pilot sleeve can smoothly contact the bone through a 1-cm skin incision. After confirming the trajectory accuracy on the workstation, a guide pin was drilled into the L5 pedicle (Fig. 4). In order to keep the consistency of the actual and planned trajectory, TiRobot was able to recalibrate the trajectory repeatedly in the process of the guide pin insertion, maintaining the positioning accuracy less than 1-mm. After verifying the pin's position with fluoroscopic images, we fixed a polyaxial cannulated pedicle screw with the diameter of 6-mm and the length of 4.5- to 5-cm. The following step was to expose the ipsilateral posterior superior iliac spine (PSIP) through another 3-cm incision. After resecting part of the bone to avoid the eminence of the screw, we inserted a polyaxial iliac screw with the diameter of 7-mm and the length of 8- to 10-cm along the medial and lateral lamina, keeping the direction to the anterior inferior iliac spine (Fig. 5). A contoured rod was percutaneously inserted to engaged the L5 pedicle screw and the iliac screw (Fig. 6). If there is rotational displacement in the pelvic ring, a partial threaded Schantz pin temporarily screwed into the iliac crest, as a "joy stick", is appropriate for reduction. As for sacral fractures with vertical displacement, longitudinal traction and distraction clamps are crucial (Fig. 7). Once completing reduction, all connectors were locked.

To insert the sacroiliac screw, we changed another appropriate locator at the end of the robotic arm, and then fixed a matched tracker at the contralateral PSIP percutaneously. Intraoperative pelvic images, including inlet, outlet and lateral views, were obtained using the C-arm machine and imported into the workstation for planning the trajectory of S1 screw (Fig. 8). After that, we drilled a guide pin into the S1 corridor with robotic assistance (Fig. 9). A cannulated screw with an appropriate length was implanted to eliminate the fracture gap and maintain the horizontal stability. It is important to note that all connectors need to be loosened and retightened immediately in the end for relieving the longitudinal distraction acting on the ipsilateral L5/S1 disk. Finally, after the C-arm machine examination confirmed that the fracture and implant position were satisfactory, the incisions were irrigated and sutured. If the affected L5/S1 facet cannot be anatomically reconstructed, autologous bone transplanted from the ipsilateral PSIS is necessary for fusion.

The Surgical Procedure Of Patients In The Conventional Group

Patients in the conventional group were placed in the same prone position. The L5/S1 superior facet joint and the ipsilateral posterior superior iliac spine (PSIS), as well as the posterior fracture line of the affected sacrum were exposed through a posterior middle longitudinal incision with the length of 10- to 12-cm. The L5 pedicle screw and iliac screw were inserted under direct vision, and then the reduction was performed. Finally, under the fluoroscopy of the C-arm machine, the guide pin and the sacroiliac screw were implanted successively through a 1-cm incision with free-hand technique. Fusion of the affected L5/S1 facet needs to be carried out according to the same principles of the robot group.

Postoperative Management

Postoperative identical managements were performed for patients in both groups. Within 48 hours after operation, the first-generation cephalosporin was routinely administered to prevent wound infection. Immediate mobilization except weight-bearing was allowed. Then all patients were transferred to the rehabilitation department for further function exercise. The intraoperative and postoperative indicators, such as operation time and fluoroscopy times, were recorded.

Maximum residual displacement was evaluated according to postoperative radiographs and was classified as excellent (0–5 mm), good, (6–10 mm), fair (11–15 mm), and poor (> 15mm) by Lindahl et al [20]. The position of the pedicle and sacroiliac screw was assessed with postoperative CT scans according to the modified Gras classification [21], which includes as follows: grade I, a screw is totally in the cancellous bone (satisfactory position); grade II, a screw is still in the bone structures, cutting the cortical bone (secure position); grade III, a screw has penetrated the cortical bone (misplaced position). Fracture healing was evaluated according to the clinical and radiological results at each follow-up. The function outcomes were investigated with Majeed's scoring system (excellent (85–100), good (70–84), fair (55–69), and poor (< 55)) [22] at the final follow-up at least 12 months after surgery.

Statistical analysis

Statistical analysis was performed using SPSS version 20.0 (SPSS Inc., Chicago, IL, USA). Measurement data such as ages were presented as mean $\pm$ standard deviation (SD) and compared using independent samples t-test. Count data such as gender were compared using chi-square or Fisher analysis. A statistically significant difference was accepted for P-values of < 0.05.

Results

There were 11 patients in the robot group and 17 patients in the conventional group. The demographic data of the two groups revealed no significant differences in this study (Table 1).

Table 1
Patients' demographics and characteristics.

characteristics	Robot group (n = 11)	Conventional group (n = 17)	<i>t</i> / χ^2	<i>P</i> value
Age(year), M $\pm$ SD	40.7 $\pm$ 12.7	39.8 $\pm$ 11.2	<i>t</i> = 0.211	0.834
Gender, n(%)	7(63.6%)	9(52.9%)	χ^2 = 0.312	0.705
Male	4(36.4%)	8(47.1%)		
Female				
Isler classification, n(%)	1(9.1%)	3(17.6%)	χ^2 = 1.315	0.613
I	7(63.6%)	12(70.6%)		
II	3(27.3%)	2(11.8%)		
III				
Tile classification, n(%)	3(27.2%)	3(17.6%)	χ^2 = 0.368	0.653
Type B	8(72.8%)	14(82.4%)		
Type C				
Time to surgery(day)	7.3 $\pm$ 5.6	7.2 $\pm$ 4.7	<i>t</i> = 0.049	0.961
Follow up (month)	18.9 $\pm$ 5.3	18.1 $\pm$ 6.1	<i>t</i> = 0.348	0.730

USFs involving LSJIs of all patients in the two groups were reduced and stabilized with TOS. Anterior pelvic ring injuries were performed with internal fixation. Of 22 patients with ramus fractures, 11 were treated with open reduction and plating fixation through the Pararectus approach (Fig. 10), while the rest were performed with close reduction percutaneous superior pubic ramus screw or anterior subcutaneous internal fixator (INFIX) fixation (Fig. 11). The symphyseal disruption in 4 patients was fixed with a construction locking plate through the Pfannenstiel approach. The two patients of symphyseal disruption in combination with rami fractures underwent open reduction and plating fixation through the Stoppa and iliac approaches.

No intraoperative neurovascular damage occurred in all patients. The intraoperative and postoperative indicators of the two groups were compared (Table 2). The average operation time of posterior pelvic ring (disinfection to closure) was 94.6 $\pm$ 21.8 min in the robot group and 112.7 $\pm$ 18.6 min in the conventional group (*P* = 0.027). The amount of surgical bleeding was 98.2 $\pm$ 36.1 ml in the robot group and 286.8 $\pm$ 92.7 ml in the conventional group, revealing a significant difference in this study (*P* < 0.001). The intraoperative fluoroscopy times were 24.1 $\pm$ 6.3 in the robot group and 34.1 $\pm$ 8.4 in the conventional group with a significant difference (*P* = 0.002). Patients in the conventional group had a longer hospital stay, compared to the robot group (*P* = 0.044).

Table 2
Results comparison between the two groups.

characteristics	Robot group	Conventional group	t/χ^2	P value
Operation time of the posterior pelvic ring (min), $M \pm SD$	94.6 ± 21.8	112.7 ± 18.6	$t=-2.347$	0.027
The amount of surgical bleeding (mm)	98.2 ± 36.1	286.8 ± 92.7	$t=-6.408$	< 0.001
Intraoperative fluoroscopy times, $M \pm SD$	24.1 ± 6.3	34.1 ± 8.4	$t=-3.386$	0.002
Maximum residual displacement excellent (0–5 mm) good (6–10 mm)	9(81.8%) 2(18.2%)	16(82.4%) 1(17.6%)	$\chi^2 = 1.056$	0.543
Gras criterion on evaluation of sacroiliac screw position, n(%) Grade I Grade II and III	10(90.9%) 1(9.1%)	12(70.6%) 5(29.4%)	$\chi^2 = 1.638$	0.355
Hospital stay(day)	14.2 ± 5.4	21.0 ± 8.4	$t=-2.133$	0.044
Healing time of sacral fractures (month)	3.7 ± 1.5	4.9 ± 1.2	$t=-2.173$	0.041
Majeed score	90.7 ± 5.6	85.5 ± 5.6	$t= 2.199$	0.039

Postoperative maximum residual displacement of the pelvic fractures in the robot group was excellent in 9 patients and good in 2 patients, while that in the conventional group was 14 and 3, respectively ($P = 0.971$). According to the screw position evaluated with the modified Gras criterion, pedicle screws fixed in all patients were in the cancellous bone, meeting grade I (satisfactory position). There were 10 sacroiliac screws with grade I and 1 with grade II in the robot group, and 12 with grade I and 4 with grade II (secure position) in the conventional group. One sacroiliac screw in the conventional group penetrated the cortical bone (grade III, misplaced position), without clinical symptoms of vascular or neurovascular impairment. No statistically difference was shown on the screw position between the two groups ($P = 0.355$), but the grade I rates were 90.9% (10/11) vs 70.6% (12/17). All the L5 pedicle screws were in the cancellous bone with grade I in the two groups.

Three patients (2 in the robot group and 1 in the conventional group) complained of slight pain at PSIS in the supine position due to prominent implants. The rate of complications relating to the incisions was 0% (0/11) in the robot group and 11.8% (2/17) in the conventional group. No wound infection was noted in the robot group, while one patient in the conventional group suffered with a deep infection. After thorough debridement and frequent dressing changing, purulence was eliminated. In the conventional group, local

hematoma in the deep wound developed in one patient, and the symptoms disappeared after puncture and drainage.

No fracture reduction loss and hardware loosening were observed at follow-ups. After 3–6 months' conservative treatment with oral medication, 4 out of 5 patients with initial neurologic impairment obtained full recovery, while the remaining one patient revealed partial improvement. All sacral fractures appeared as bone union within six months. The mean healing time was 3.7 ± 1.5 months in the robot group and 4.9 ± 1.2 months in the conventional group, with the healing time exhibiting a statistical difference ($P = 0.041$). The Majeed functional score at the final follow-up was 90.7 ± 5.6 in the robot group and 85.5 ± 5.6 in the conventional group ($P = 0.039$).

Discussion

In this study we reviewed the data of associated unilateral USF with an ipsilateral LSJI involvement that were treated with triangular osteosynthesis and compared the results of those patients with or without robotic assistance in a consecutive series.

The lumbosacral junction is a special area that transfers upper body weight to the pelvis and lower extremities through the sacrum. The conduction of axial stress can be seriously affected due to the damage in this area. There is a general consensus among orthopedic surgeons worldwide regarding triangular osteosynthesis in the treatment of vertically USFs, especially with LSJIs [5–10]. To avoid the excessive dissection of the soft tissue, controllable and precise functionalization of minimally invasive surgery with free-hand technique on pelvic fractures remains a major challenge, despite considerable progress. Until recently, pelvic fracture surgeries with robotic assistance demonstrate significant benefits in the operating room for the patients and surgical staffs, with some studies revealing that robot-aided surgeries had higher accuracy for screw implantation and lower radiation exposure than fluoroscopy-guided free-hand surgeries [23]. In a study of 33 osteoporosis patients with sacral fractures, the authors compared robot-aided to conventional free-hand sacroiliac screw fixation. They found that robotic assistance led to higher rates of screw placement accuracy, with the robot-aided group demonstrating an accuracy of 94.4% (vs 73.3%), using accuracy criterion previously set by Gras et al [17].

In our study, the actual position of the pedicle and sacroiliac screws in the two groups, were compared to evaluate the accuracy. According to the assessment from the postoperative CT images, we found that pedicle screws in both groups were all in the vertebral bodies, indicating that L5 pedicle screws can be accurately implanted with or without TiRobot assistance. There were 5 sacroiliac screws cut the cortical bone and one sacroiliac screw penetrated the cortex in the conventional group, while all the screws in the robot group were in the cancellous bone. Due to the limited cases in this study, there was no statistical difference in the accuracy of screw implantation. However, the percentage of Gras grade I in the two groups was still significantly discrepant (90.9% vs 70.6%), indicating that sacroiliac screw insertion can be very demanding with free-hand technique. In the process of guide pin implantation, it's difficult to slightly adjust the pin's direction, and frequent drillings will increase the risk of neurovascular injury and

have a direct impact on the fixation strength. Consequently, experienced surgeons usually don't adjust the guide pin when using free-hand technique once the position is acceptable.

Additionally, because bony landmarks identified in the process of the guide pin insertion often need to be visualized with fluoroscopy, patients and medical staffs are subject to large amounts of radiation. According to recorded frequency of intraoperative fluoroscopy, the data in this study were significantly decreased in the robot group ($P < 0.001$), which was similar to the existing reports using the same technique [16, 17, 24]. All guide pins in the robot group were basically successfully implanted at one time, while that in the conventional group needs to be adjusted twice or more.

Minimally invasive surgery usually performs indirect reduction without exposing fractures, so as to decrease the amount of bleeding and shorten the suture time. In this study, the length of surgical incision assisted by TiRobot was much smaller than that in the conventional group, demonstrating the differences of soft tissue damage in patients of the two groups. Three skin incisions above the implanted screws, including the pedicle, iliac and sacroiliac screws, were necessary for the unilateral USF involving an ipsilateral LSJI. For each patient in the conventional group, we made a posterior median longitudinal incision with the length of 10–12 cm followed by the dissected paravertebral muscles for screw implantation under direct vision, which inevitably led to more invasion than that in the robot group. In addition, further destruction of blood supply at fracture sites was avoided by using closed reduction, which may be the main reason why the fracture healing time in the robot group was shorter than that in the conventional group ($P < 0.041$). Although no significant difference was noted, the rate of complications relating to incisions in the robot group was much lower than that in the conventional group (0% vs 11.8%). In our view, a few cases in this study may have an impact on the analysis of clinical results, but minimally invasive surgery, after all, is significantly less invasive than conventional open surgery.

Gardner et al. reported that the S1 screw corridor is on average 36% narrower in the dysmorphic sacra compared with the normal [25]. The presence of a dysmorphic sacrum is a risk factor for inaccurate screw placement into the S1 vertebra. Accordingly, it's crucial to measure the screw corridor preoperatively, especially the dimension of the sacral vestibule, leading to determine if a cannulated screw with the diameter of 6.5mm could be accommodated, even though TiRobot enabled safer screw insertion into the dysmorphic sacra. Different from traditional navigation, the TiRobot system can monitor the trajectory in the process of guide pin implantation and identify the errors in real time. Also, it only takes approximately one minute to re-plan the screw path in case of the guide pin with an unsatisfactory position. Unlike the matching failures occurred in CT or 3D fluoroscopic navigations, the TiRobot system can ensure that screw planning won't be affected by the change of fracture position, only keeping the tracker on the patient side to be identified consistently [26].

As an upgrade of navigation, TiRobot is not omnipotent. After all, it doesn't have the reduction function. Poor fracture reduction can significantly reduce the 3D available space of the screw corridor. Improving the reduction quality, especially the anatomical reduction at the narrowest part of the corridor, is an

important guarantee for safe and effective screw placement. Also, orthopedic robotic surgery is not without its disadvantages. TiRobot is cumbersome with high initial costs, and the use of the robotic machine necessitates professionals or additional training. The lack of reliable tactile feedback system can only be compensated by surgeons' visual information, which is a common deficiency of current surgical robots, including TiRobot.

This study, however, has several limitations. Robot-aided surgery is still mostly confined to some large hospitals and has, to date, not seen wide adoption in orthopedics. In addition, the cases demonstrated are all in our institution, and too small sample size in this study may lead to the inaccuracy of outcome comparison. More comparative studies between robot-aided surgery and conventional open surgery were needed in multicenter for better evidence of USFs involving LSJIs. Therefore, further clinical assessment necessitates to improve the authority of these conclusions and define its future applications, limitations, and developed directions.

Conclusion

To sum up, compared with open reduction, minimally invasive triangular osteosynthesis with robotic assistance can be an effective treatment for the unilateral USF involving an ipsilateral LSJI, with the significant advantages of less damage and less incision-related complications. When considering direct benefits, high accuracy and low radiation dependence, orthopaedic robots are more recommended. The primary factor preventing it from being cost-effective is the high price of the machine. However, we believe that minimally invasive surgery with robotic assistance will become more beneficial for orthopedic surgeons and patients in the near future.

Abbreviations

TOS: Triangular osteosynthesis; USFs: Unstable sacral fractures; LSJIs: Lumbosacral junction injuries; CT: Computed tomography; 3D: Three dimensional; PSIS: Posterior superior iliac spine; INFIX: Anterior subcutaneous internal fixator

Declarations

Availability of data and materials

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

Code availability

Some or all code generated or used during the study are available from the corresponding author by request.

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Not applicable.

Authors' Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [ZJ L], [Y G] and [JJ]. The first draft of the manuscript was written by [ZJ L] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Ethical approval and Consent to participate

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (the Ethics Committee of Tianjin Hospital in Tianjin City) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The signed informed consent was obtained from the patients in the study.

Consent to publication

The authors would like to declare that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Competing interests

The authors declare that they have no competing interests.

References

- [1] Oransky M, Gasparini G (1997) Associated lumbosacral junction injuries (LSJIs) in pelvic fractures. *J Orthop Trauma* 11:509–512. <https://doi.org/10.1097/00005131-199710000-00008>.
- [2] Isler B(1990) Lumbosacral lesions associated with pelvic ring injuries. *J Orthop Trauma* 4:1–6. <https://doi.org/10.1097/00005131-199003000-00001>.
- [3] Iorio JA, Jakoi AM, Rehman S (2015)Percutaneous sacroiliac screw fixation of the posterior pelvic ring. *Orthop Clin North Am*46:511–521. <https://doi.org/10.1016/j.ocl.2015.06.005>.
- [4] Acklin YP, Marco G, Sommer C (2015) Double locking plate fixation of sacral fractures in unstable pelvic ring C-type injuries. *OperOrthopTraumatol* 27:74-79. <https://doi.org/10.1007/s00064-014-0307-2>.

- [5] Kach K, Trentz O (1994) Distraction spondylodesis of the sacrum in “vertical shear lesions” of the pelvis. *Unfallchirurg*97:28-38. <https://doi.org/10.1097/00007890-199401001-00030>.
- [6] Schildhauer TA, Ledoux WR, Chapman JR, Henley MB, Tencer AF, Routt ML Jr (2003) Triangular osteosynthesis and iliosacral screw fixation for unstable sacral fractures: a cadaveric and biomechanical evaluation under cyclic loads. *J Orthop Trauma*17:22-31. <https://doi.org/10.1097/00005131-200301000-00004>.
- [7] Schildhauer TA, Josten Ch, Muhr G (2006) Triangular osteosynthesis of vertically unstable sacrum fractures: a new concept allowing early weight-bearing. *J Orthop Trauma*20:S44-51. <https://doi.org/10.1097/00005131-199806000-00002>.
- [8] Acklin YP, Zderic I, Richards RG, Schmitz P, Gueorguiev B, Grechenig S (2018) Biomechanical investigation of four different fixation techniques in sacrum Denis type II fracture with low bone mineral density. *J Orthop Res*36:1624-1629. <https://doi.org/10.1002/jor.23798>.
- [9] Berber O, Amis AA, Day AC (2011) Biomechanical testing of a concept of posterior pelvic reconstruction in rotationally and vertically unstable fractures. *J Bone Joint Surg Br* 93:237-244. <https://doi.org/10.1302/0301-620X.93B2.24567>.
- [10] Sagi HC, Militano U, Caron T, Lindvall E (2009) A comprehensive analysis with minimum 1-year follow-up of vertically unstable transforaminal sacral fractures treated with triangular osteosynthesis. *J Orthop Trauma*23:313-321. <https://doi.org/10.1097/BOT.0b013e3181a32b91>.
- [11] Bellabarba C, Schildhauer TA, Vaccaro AR, Chapman JR (2006) Complications associated with surgical stabilization of high-grade sacral fracture dislocations with spinopelvic instability. *Spine (Phila Pa 1976)*31:S80-88. <https://doi.org/10.1097/01.brs.0000217949.31762.be>.
- [12] Tan GQ, He JL, Fu BS, Li LX, Wang BM, Zhou DS (2012) Lumbopelvic fixation for multiplanar sacral fractures with spinopelvic instability. *Injury*43:1318-1325. <https://doi.org/10.1016/j.injury.2012.05.003>.
- [13] Templeman D, Schmidt A, Freese J, Weisman I (1996) Proximity of iliosacral screws to neurovascular structures after internal fixation. *Clin Orthop Relat Res* 329:194-198. <https://doi.org/10.1097/00003086-199608000-00023>.
- [14] Hinsche AF, Giannoudis PV, Smith RM (2002) Fluoroscopy-based multiplanar image guidance for insertion of sacroiliac screws. *Clin Orthop Relat Res* 395:135-144. <https://doi.org/10.1097/00003086-200202000-00014>.
- [15] Wang JQ, Wang Y, Feng Y, Han W, Su YG, Liu WY (2017) Percutaneous sacroiliac screw placement: a prospective randomized comparison of robot-assisted navigation procedures with a conventional technique. *Chin Med J (Engl)*130:2527-2534. <https://doi.org/10.4103/0366-6999.217080>.

- [16] Liu ZJ, Hu YC, Tian W, Jin X, Qi HT, Sun YX(2021) Robot-aided minimally invasive lumbopelvic fixation in treatment of traumatic spinopelvic dissociation. *Orthop Surg* 13:563-572. <https://doi.org/10.1111/os.12908>.
- [17] Liu ZJ, Gu Y, Jin X, Tian W, Qi HT, Sun YX (2021) Comparison of outcomes following TiRobot-assisted sacroiliac screw fixation with bone grafting and traditional screw fixation without bone grafting for unstable osteoporotic sacral fracture: a single-center retrospective study of 33 patients. *Med Sci Monit* 27:e932724. <https://doi.org/10.12659/MSM.932724>.
- [18] Gibbons KJ, Soloniuk DS, Razack N (1990) Neurological injury and patterns of sacral fractures. *J Neurosurg* 72: 889-893. <https://doi.org/10.3171/jns.1990.72.6.0889>.
- [19] Tile M (1988) Pelvic ring fractures: should they be fixed? *J Bone Joint Surg Br* 70:1-12. <https://doi.org/10.1302/0301-620X.70B1.3276697>.
- [20] Lindahl J, Hirvensalo E, Bostman O, Santavirta S (1999) Failure of reduction with an external fixator in the management of injuries of the pelvic ring. Long-term evaluation of 110 patients. *J Bone Joint Surg Br* 81:955-962. <https://doi.org/10.1302/0301-620x.81b6.8571>.
- [21] Gras F, Marintschev I, Wilharm A, Klos K, Mückley T, Hofmann GO (2010) 2D-fluoroscopic navigated percutaneous screw fixation of pelvic ring injuries-a case series. *BMC MusculoskeletDisord* 11:153. <https://doi.org/10.1186/1471-2474-11-153>.
- [22] Majeed SA (1989) Grading the outcome of pelvic fractures. *J Bone Joint Surg Br* 71:304-306. <https://doi.org/10.1007/BF02471596>.
- [23] Karthik K, Colegate-Stone T, Dasgupta P, Tavakkolizadeh A, Sinha J (2015) Robotic surgery in trauma and orthopaedics: a systematic review. *Bone Joint J* 97-B: 292-299. <https://doi.org/10.1302/0301-620X.97B3.35107>.
- [24] Long T, Li KN, Gao JH, Liu TH, Mu JS, Wang XJ(2019) Comparative study of percutaneous sacroiliac screw with or without TiRobot assistance for treating pelvic posterior ring fractures. *Orthop Surg* 11:386-396. <https://doi.org/10.1111/os.12461>.
- [25] Gardner MJ, Morshed S, Nork SE, Ricci WM, Chip Routt ML Jr (2010) Quantification of the upper and second sacral segment safe zones in normal and dysmorphic sacra. *J Orthop Trauma* 24:622-629. <https://doi.org/10.1097/BOT.0b013e3181cf0404>.
- [26] Takao M, Hamada H, Sakai T, Sugano N (2019) Factors influencing the accuracy of iliosacral screw insertion using 3D fluoroscopic navigation. *Arch Orthop Trauma Surg* 139:189-195. <https://doi.org/10.1007/s00402-018-3055-1>.

Figures

Figure 1

The TiRobot system

Figure 2

The positioning device(the locator) on the right and the fixed tracker on the left

Figure 3

Trajectory planning of the unilateral pedicle screw on L5

Figure 4

Guide pin drilling under the guidance of the robotic arm

Figure 5

Implantation of a polyaxial iliac screw

Figure 6

Insertion of a connection rod

Figure 7

Reduction of the sacral fracture

Figure 8

Trajectory planning of the ipsilateral sacroiliac screw on S1

Figure 9

Insertion of a guide pin into the S1 screw corridor with TiRobot assistance

Figure 10

Male, 26-years-old, crush injury. A. Radiograph on admission showing a displaced pelvic fracture due to the lateral compression mechanism. B The CT reconstruction image revealing an internally rotated displaced sacral fracture combined with ipsilateral rami fractures (a Tile type B2) on left. C-E The area in the red circles on CT views revealing L5/S1 facet fracture and subluxation (a LSJI type IIc). F The skin incisions of posterior pelvic ring after minimally invasive TOS with TiRobot assistance. G 3D CT scan taken postoperatively. H Postoperative axial CT view of S1 demonstrating satisfactory position of the sacroiliac screw. I Radiograph at 6 months post-operative showing fractures were union.

Figure 11

Female, 34-years-old, a fall from height. A,B Three-dimensional CT scan and radiograph on admission showing a vertically displaced sacral fracture associated with bilateral rami fractures (a Tile type C1) with a comminuted subtrochanteric fracture on right. C,D The area in the red circles on CT views revealing a LSJI of type IIb on right. E The surgical incisions of posterior pelvic ring after minimally invasive TOS with TiRobot assistance. F Three-dimensional CT scan taken postoperatively: anterior pelvic ring was stabilized by INFIX and the pelvic fracture was achieved satisfactory reduction. G,H Axial CT view of L5 and S1 area demonstrating the pedicle and sacroiliac screws were both in the cancellous bone. I Radiograph at 6 months post-operative showing fractures were union.