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RESEARCH ARTICLE

Finite Element Analysis and Transiliac-Transsacral Screw Fixation for Posterior Pelvic Ring with Sacrum Dysplasia

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Objective: Posterior pelvic ring sacroiliac screws are preferred by clinicians for their good biomechanical performance. However, there are few studies on mechanical analysis and intraoperative screw insertion of the dysplastic sacrum and sacroiliac screw. This study investigated the biomechanical performance of oblique sacroiliac screws (OSS) in S1 combined with transiliac-transsacral screws (TTSs) in S2 for pelvic fracture or sacroiliac dislocation with dysplastic sacrum and evaluated the safety of screw placement assisted by the navigation template.

Methods: Six models were established, including one OSS fixation in the S2 segment, one transverse sacroiliac screw (TSS) fixation in the S2 segment, one TTS fixation in the S2 segment, one OSS fixation in the S1 and S2 segments, one OSS fixation in the S1 segment and one TSS fixation in the S2 segment, one OSS fixation in the S1 segment and one TTS fixation in the S2 segment. Then, finite element analysis (FEA) was performed. Twelve dysplastic sacrum patients with pelvis fracture or sacroiliac dislocation underwent OSS insertion in the S1 combined with TTS insertion in the S2 under the assistance of the patient-specific locked navigation template. Grading and Matta scores were evaluated after surgery.

Results: In the one-screw fixation group, the vertical displacements of the sacrum surface of S2 OSS, S2 TSS and S2 TTS were 1.23, 1.42, and 1.22 mm, respectively, and the maximum stress of screw were 139.45 MPa, 144.81 MPa, 126.14 MPa, respectively. In the two-screw fixation group, the vertical displacements of the sacrum surface of the S1 OSS + S2 OSS, S1 OSS + S2 TSS and S1 OSS + S2 TTS were 0.91, 1.06, and 0.75 mm, respectively, and the maximum stress of screw were 149.26 MPa, 167.13 Pa, 136.76 MPa, respectively. Clinically, a total of 12 TTS and OSS were inserted under the assistance of navigation templates, with a surgical time of 55 ± 7.69 min, bleeding of 57.5 ± 18.15 ml and radiation times of 14.5 ± 4.95. One of the TTS and one of the OSS were grade 1, and the other screws were grade 0. The Matta scores of nine patients were excellent, and three patents were good.

Conclusion: OSS in the S1 combined with TTS in the S2 had the best mechanical stability in six models, and it is safe for screw insertion assisted by the patient-specific locked navigation template.

Key words: 3D printing; Dysplasia sacrum; FEA; Pelvic ring injuries; Transverse sacroiliac screw

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Introduction

Pelvic ring injuries due to high-energy trauma are devastating and are often associated with complex concomitant injuries; they also have high rates of morbidity and mortality.[1] Posterior pelvic ring sacroiliac screws are preferred by clinicians because they are less invasive than plate screw systems;[2] however, free-hand insertion of sacroiliac screws tends to result in more radiation exposure and neurologic damage.[3] The emergence of navigation technology could be a solution to the above problems, and scholars have found that sacroiliac screw implantation assisted by robot and 3D-printed templates can significantly shorten patients' operation time, reduce patients' radiation exposure, and improve safety and accuracy.[4,5] For patients with osteoporosis, significant posterior pelvic instability, including spinopelvic dissociation, obesity, anticipated noncompliant behavior, bilateral posterior pelvic injuries, and nonunion procedures, transiliac-transsacral screws (TTSs) that traverse the bilateral sacroiliac joints and sacral body have been reported to have better mechanical properties and can provide better pelvic stabilization than other options.[6] In addition, TTSs do not adversely affect or improve patient outcomes or subjective pain scores when compared with those treated with unilateral sacroiliac screws.[7]

Dysmorphic osseous characteristics include colinearity of the upper portion of the sacrum and the iliac crests on the outlet radiographic view as well as the presence of mammillary bodies at the sacral ala, noncircular anterior sacral foramina, residual upper sacral disks, a tongue-in-groove sacroiliac joint surface, and cortical indentation of the ala on the inlet radiograph.

Due to the anatomical variation of the upper sacral, manifested as a more elevated S1 segment,[8] it is often impossible for 7.3 mm diameter TTS placement in the S1 segment. It has been reported that 16.7% of patients cannot accommodate the TTS in the S1 segment,[1] but this almost never happens with the TTS in the S2 segment. However, there have been few studies on mechanical analysis and intraoperative screw insertion of the dysplastic sacrum and sacroiliac screw. Therefore, a pelvic ring injury model caused by sacral and pubic fracture from a healthy male with a dysplastic sacrum was established. Then, different types of sacroiliac screws were inserted for posterior pelvic fracture and combined with a minimally invasive anterior pelvic ring internal fixator (Infix) for anterior pelvic fracture. Then, finite element analysis (FEA) was used to evaluate the mechanical performance of the fixation. This paper aimed to: (i) research the ideal sacroiliac screw fixation method for pelvic fracture or sacroiliac dislocation with sacral dysplasia by using FEA; and (ii) find a method for screw insertion quickly and safely and evaluate the feasibility of locked navigation templates for sacroiliac screw insertion.

Materials and Methods

Establishment of the Finite Element Model

A 29-year-old healthy male was selected from the PACS system of the Zigong Fourth People's Hospital with sacral dysplasia (174 cm in height, 74 kg in weight, BMI = 24.51). Additionally, 128-slice computed tomography (Siemens SOMATOM Force, Germany) was performed for pelvic scanning with a scan thickness of 0.625 mm, and the original data for bone reconstruction were obtained in DICOM format. The pelvic model was established by using Mimics Research 22.0 (Materialise, Leuven, Belgium). Noise reduction and smooth optimization were carried out in Geomagic Wrap 2017 (3DS System, USA). SolidWorks 2016 (Dassault Systemes S.A., USA) software was used to establish cortical bone, cancellous bone, cartilage of sacroiliac articular and pubic symphysis (Fig. 1A). The main ligaments of the model were simulated by tension-only spring elements, which included anterior and posterior sacroiliac, interosseous sacroiliac, sacrotuberous, sacrospinous and superior pubic ligaments (Table 1). The liner, elastic and isotropic material properties were assigned to all parts of the model, and the parameters of the elasticity modulus and Poisson's ratio were set according to a previous study, as listed in Table 1.[9] To improve the accuracy of the FE model, the quadratic

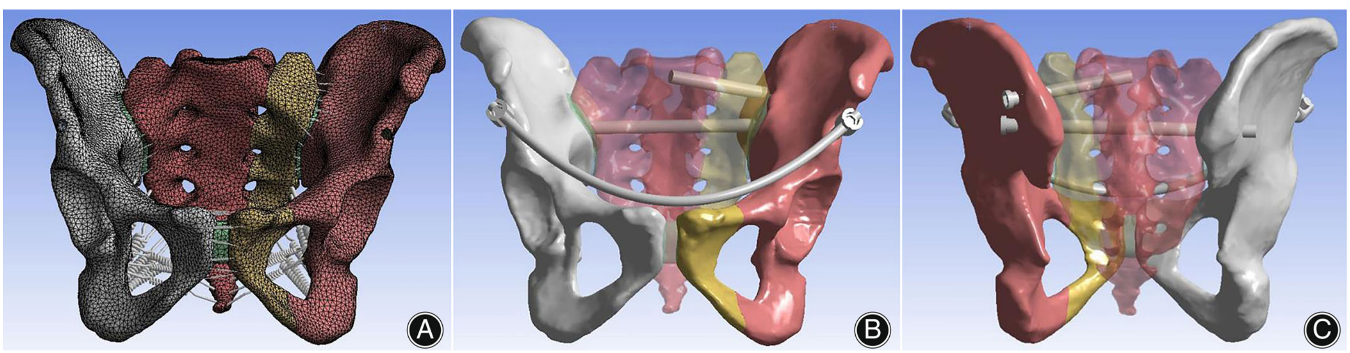

Fig. 1 (A) Tile C-type pelvic fracture models were established. (B, C) The anterior pelvic ring internal fixator, oblique sacroiliac screw and transiliac-transsacral screw were inserted, as shown in the anterior view and posterior view.

TABLE 1 Material properties of the current FE model

	Elastic modulus (MPa)	Poisson coefficient	Stiffness (N/mm)	Number of springs
Cortical bone	17 000	0.3	–	–
Cancellous bone	150	0.3	–	–
Interpubic disc	5	0.45	–	–
Articular cartilage	11.9	0.4	–	–
Anterior sacroiliac	–	–	700	27
Posterior sacroiliac	–	–	1400	15
Interosseous sacroiliac	–	–	2800	8
Sacrotuberous	–	–	1500	15
Sacrospinous	–	–	1400	10
Superior pubic	–	–	500	24
Screw and rod	110 000	0.3	–	–

tetrahedron (Tetra 10) element type was used in the mesh part. The mesh size was controlled at 2–3 mm in iliac bone and 1–1.5 mm in the implants and screw-to-bone contact place. After several iterations of testing, the element quality (average 0.58), aspect ratio (99% elements >5) and Jacobian ratio (average − 0.16) were used to control the meshing quality in a reasonable range.

Six Types of Fixation Methods

Tile C pelvic fracture models (Dennis II type fracture) were established by sacral foramectomy combined with resection of the superior and inferior rami of the pubis. The internal fixator used in this study included anterior pelvic ring internal fixators (Fig. 1B), sacroiliac screws (length of 70 mm, diameter of 7.3 mm) and TTS (length of 150 mm, diameter of 7.3 mm) (Fig. 1C). We conducted six internal fixation models, which were all disposed of by INFIX for the fracture of the superior and inferior rami of the pubis, while different fixation methods were adopted for sacrum fractures. (A) One oblique sacroiliac screw fixation in the S2 segment (S2 OSS) (Fig. 2A). (B) One transverse sacroiliac screw fixation in the S2 segment (S2 TSS) (Fig. 2B). (C) One TTS fixation in the S2 segment (S2 TTS) (Fig. 2C). (D) One OSS fixation in the S1 and S2 segments. (S1 OSS + S2 OSS) (Fig. 2D). (E) One OSS fixation in the S1 segment and one TSS fixation in the S2 segment (S1 OSS + S2 TSS) (Fig. 2E). (F) One OSS fixation in the S1 segment and one TTS fixation in the S2 segment (S1 OSS + S2 TTS) (Fig. 2F).

Contact, Constraint, and Loading Condition

The face-to-face contact was set for the sacroiliac joints, fracture contact surface and the thread part of the screw to bone, and the contact type was set as frictional with a coefficient of 0.3. The head part of the screw-to-bone contact was set as bonded as well as the other contacts of the model. Both sides of the acetabulum were fully constrained in six degrees of freedom, and a vertical downward loading force of 600 N was applied on the upper surface of the sacrum to simulate a

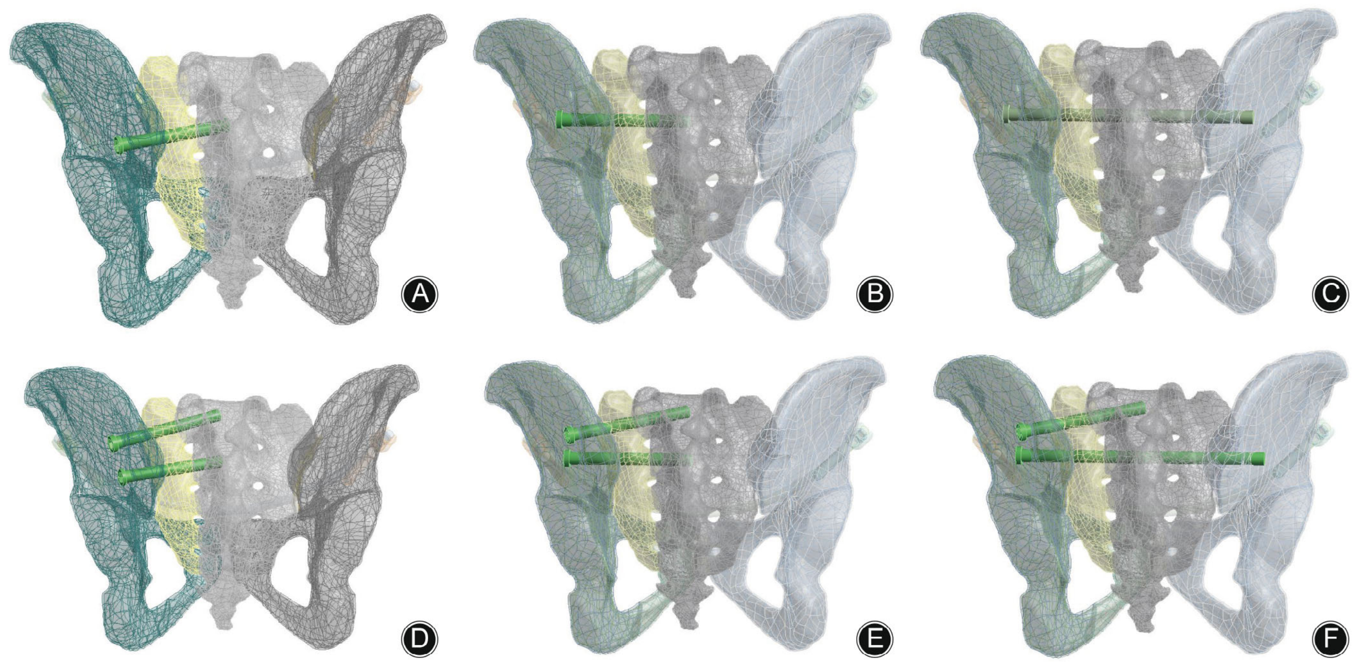

Fig. 2 (A) One oblique sacroiliac screw was inserted in S2. (B) One transverse sacroiliac screw was inserted in the S2 segment. (C) One transiliac-transsacral screw was inserted in the S2 segment. (D) Two oblique sacroiliac screws were inserted in the S1 and S2 segments. (E) One oblique sacroiliac screw was inserted in the S1 segment, and one transverse sacroiliac screw was inserted in the S2 segment. (F) One oblique sacroiliac screw was inserted in the S1 segment, and one transiliac-transsacral screw was inserted in the S2 segment.

double-leg standing posture.[10] For postprocessing, the maximum von Mises stress of the implants and the vertical displacement of the upper surface of the sacrum were recorded to reveal the biomechanical properties among the models.

Patient Preparation

We retrospectively identified patients treated with TTS at the S2 segment and OSS at the S1 segment from May 2018 to February 2019 and enrolled them in our trauma center's database. The inclusion criteria were as follows: (i) definite sacral fracture or sacroiliac dislocation; (ii) sacrum dysplasia with a TTS corridor diameter greater than 10 mm; (iii) reducible sacral fracture and sacroiliac dislocation; and (iv) tile classification B/C. The exclusion criteria were as follows: (i) severe systemic diseases; or (ii) open pelvic injuries.

A total of 12 patients with sacrum dysplasia were selected in this study, including eight males and four females, with an average age of 40.73 and average BMI of 23.72 (Table 2). The operations were performed by the same surgeon with more than10 years of experience.

Preoperative Preparation

All patients underwent X-ray (Fig. 3A) and CT (Fig. 3B) examinations preoperatively, and the CT data were imported into Mimics 22.0 to establish a three-dimensional model of the sacrum and pelvis (Fig. 3C). A virtual OSS and TTS with a diameter of 7.3 mm were inserted into the S1 and S2 segments, respectively (Fig. 3D). Data for the pelvic and virtual screws were entered into 3-Matic 13.0 (Materialise, Leuven, Belgium). According to the principle of the locking plate, a personalized locking navigation template base with a thickness of 3 mm was designed with the posterior superior iliac spine as the design target. Two to four holes each with a diameter of 2.7 mm were designed on the navigation template base to insert screws with a diameter of 2.5 mm so that the navigation template base could be stably attached to the bone surface. A navigation pipe with an outer diameter of 9 mm and an inner diameter of 2.6 mm was designed according to the position and direction of the virtual screw (Fig. 3E,F). The standard template library (STL) file of the navigation template base and navigation pipe was imported into 3D slicing software (accuracy, 0.014 mm; material, photosensitive resin) for printing (3DS, Project 3600, United States). The STL file of the pelvis was imported into 3D slicing software (accuracy, 0.1 mm; material, PLA+) for printing (3D Talk, FAB 460, China). The fracture models were segmented, and simulated reduction was performed by rotation and translation. Then, a simulated operation was performed before surgery to verify whether the Kirschner wire under the guidance of the individualized navigation template was consistent with the preoperative design. The navigation template was sterilized at low temperature before the operation. Preoperative traction reduction was performed in patients with displacement sacral fracture and sacroiliac dislocation.

Surgical Technique

First, an incision was created according to the size and position of the navigation template base, and soft tissue was stripped from the posterior superior iliac spine and the iliac wing (Fig. 4A). Second, the navigation template base was inserted through an incision so that the navigation template base could adhere to the anatomical position of the posterior superior iliac spine (Fig. 4B). The stability of the template was carefully checked, and the navigation template base was fixed on the bone with screws through the 2.7 mm screw hole in the base (Fig. 4E). Third, two small incisions were made at the entry point of the sacroiliac screws (Fig. 4C). Fourth, intraoperative reduction of the pelvis was performed as close as possible to the simulated reduction based on a 3D-printed model. Fifth, two Kirschner wires with a diameter of 2.5 mm were inserted into the bone along the navigation pipe. The location of the Kirschner wires was determined by fluoroscopy of the

TABLE 2 Patients' clinical data

NO.	Gender	Age (years)	BMI (kg/cm^2)	Pelvic ring disruption	Tile classfication	Surgical time (min)	Blood loss (ml)	Radiation times	Grade		Matta score
									S1	S2	
P1	Male	59	24.8	Denis I	B	50	50	13	0	0	Excellent
02	Male	45	21.8	Denis II	B	60	60	10	0	0	Excellent
03	Female	38	25.7	Denis II	C	60	50	11	0	0	Excellent
04	Male	48	23.9	Denis II	B	50	30	15	0	0	Excellent
05	Female	57	24.6	SI dislocaiton	C	70	100	25	1	1	Good
06	Male	43	21.9	Denis I	B	45	40	12	0	0	Excellent
07	Male	19	23.5	Denis I	B	50	60	16	0	0	Excellent
08	Female	46	24.6	Denis I	B	60	50	10	0	0	Excellent
09	Male	28	21.8	SI dislocaiton	C	60	50	18	0	0	Good
10	Female	47	26.9	Denis II	C	60	80	22	0	0	Good
11	Male	52	22.7	Denis I	B	45	60	10	0	0	Excellent
12	Male	25	22.4	Denis II	B	50	60	12	0	0	Excellent
Mean		40.73	23.72			55.00	57.50	14.50			
SD		11.93	1.66			7.69	18.15	4.95			

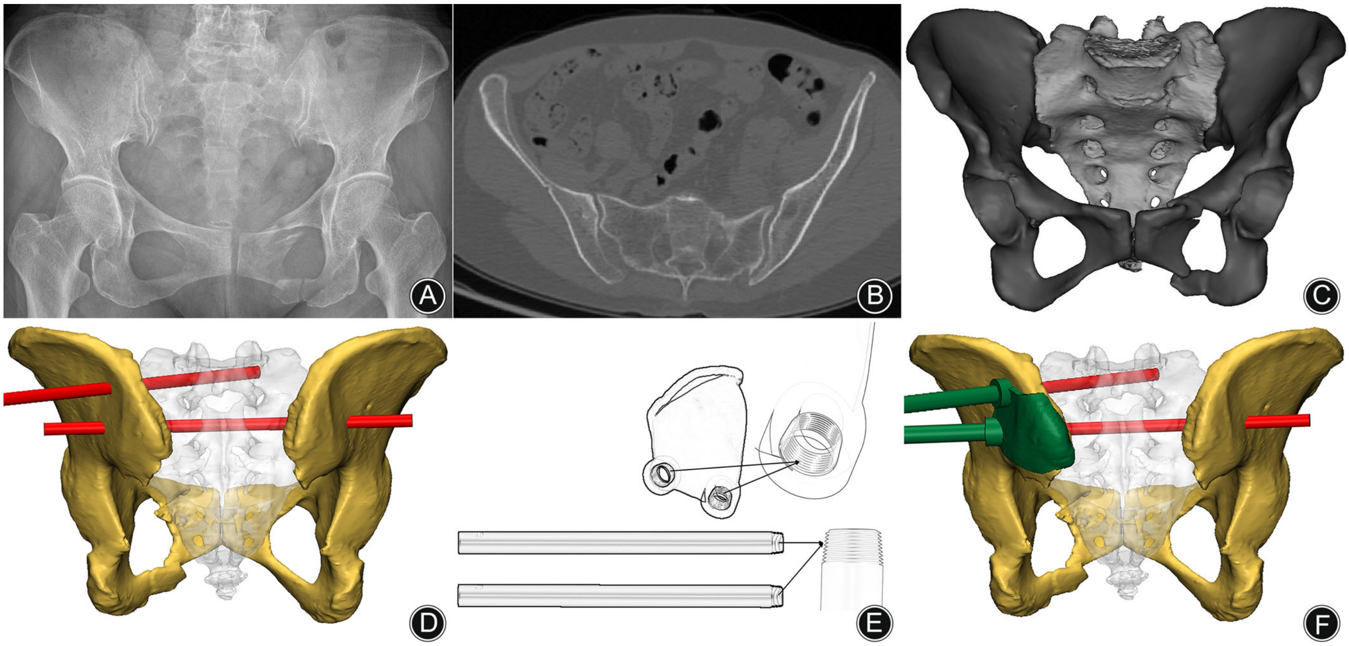

Fig. 3 One patient, 48-year-old male, with a Tile B fracture and a Dennis II fracture. (A-C) x-ray, CT, and 3D model of the preoperative pelvis. (D) An oblique sacroiliac screw and transiliac-transsacral screw with a diameter of 7.3 mm were inserted in the S1 and S2 segments. (E) Threaded structure of the navigation template in the sketch. (F) Navigation template was designed according to the position and direction of the virtual screw.

pelvic inlet, pelvic outlet and lateral sacrum (Fig. 4D) (Fig. 5A-C). Sixth, the navigation pipe was removed, and a 7.3-mm diameter cannulated screw was inserted into the sacrum along the Kirschner wires (Fig. 4F) (Fig. 5D–F) and(Fig. 4G). Finally, the Kirschner wires and navigation template base were removed, and the wound was sutured (Fig. 4H) (Fig. 5G–I).

Evaluation Criteria

Displacement distribution: (i) vertical displacement of the sacrum surface (VDS) in the six internal fixation models and the intact pelvic model was recorded, which indicated the stability of the posterior pelvis;

Von Mises stress: the maximum stress was used to find the most dangerous part of internal fixation. In addition, it could be used to compare the biomechanical properties in different fixations.

Grading score:[11] grade 0, safe insertion, screws located in cancellous bone; grade 1, cortical bone perforation <2 mm; and grade 2, cortical bone perforation greater than 2 mm. Grade 0 and 1 insertions were considered successful and safe, and grade 2 insertions indicated the possibility of nerve damage.

The quality of the reduction was assessed by Matta scores, which are defined as follows:[12] excellent, l<4 mm of fracture displacement; good, 4–10 mm of fracture displacement; and fair, 10–20 mm of fracture displacement.

Statistical Analysis

All statistical data were processed in SPSS 19.0 (SPSS Inc.; Chicago, IL, USA), and the quantitative data were expressed as the mean ± standard deviation (SD), such as age, BMI, surgical time, bleeding and radiation times.

Results

Finite Element Analysis Results

All the FE models contained approximately 165,000 elements and 304,000 nodes. The average solution time of each model was approximately 1 h. The displacement and stress results converged successfully in the convergent test. While changing the mesh size, the deviation of the displacement was controlled under 1%, and the deviation of the stress result was controlled under 5%. All the generated data are listed in Table 3. As the fracture line passed completely through the sacral foramen unilaterally, vertical instability could be represented by vertical downward displacement of the S1 upper surface. A lower displacement value indicates a higher internal fixation strength. In the one-screw fixation group, model A and model C showed similar results of 1.23 and 1.22 mm, respectively. The displacement in model B was 1.42 mm, which increased by 16% compared with models A and C. In the two-screw fixation group, model F had the lowest displacement of the S1 upper surface of 0.75 mm, which was the most stable fixation method. The displacements of model D and model E were 0.91 mm (increased by 21.3% compared

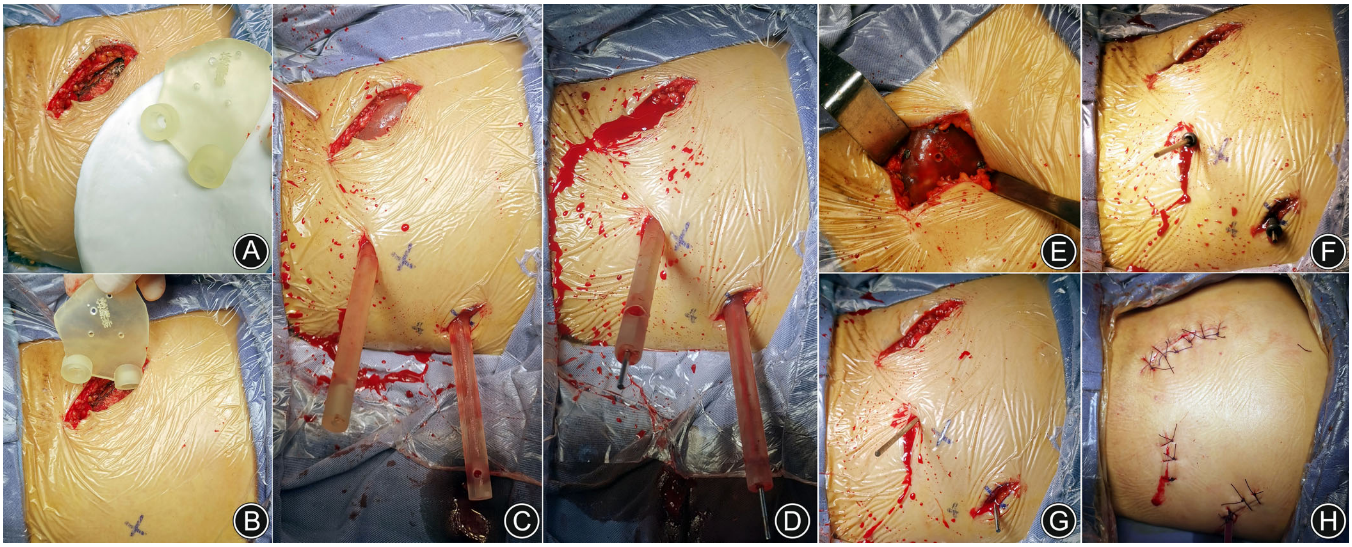

Fig. 4 Intraoperative process of the above patients. (A) The incision was made and exposed to the bone surface attached with the navigation template. (B) The navigation template base was placed. (C) The navigation pipes were inserted. (D) Two Kirschner wires with diameter of 2.5 mm were inserted into the bone along navigation pipes. (E) The navigation template base was fixed on the bone with 2.7 mm diameter screws through the hole in the base. (F) The navigation pipes were removed. (G) The 7.3-mm diameter cannulated screw were inserted into the sacrum along the Kirschner wires. (H) The Kirschner wires and navigation template base were removed, and the wound was sutured.

to model F) and 1.06 mm (increased by 41.3% compared to model F), respectively. In summary, the values ranked as model F < D < intact model < E < C < A < B (Fig. 6).

The von Mises stress can represent the stress distribution of internal fixation, and the maximum value indicates the location where internal fixation is most prone to failure and fracture. According to the contour map, the most dangerous place was located at the screw-to-bone junction. In one screw fixation group, model C had the lowest maximum stress, which was 126.14 MPa. The maximum stresses of model A and model B were 139.45 MPa (increased by 10.5% compared to model C) and 144.81 MPa (increased by 14.8% compared to model C), respectively. In the two-screw fixation group, model F had the lowest maximum stress of 136.76 MPa. The maximum stresses of model D and model E were 149.26 MPa (increased by 9.1% compared to model F) and 167.13 MPa (increased by 22.2% compared to model F), respectively. In summary, the values ranked as model C < F < A < B < D < E (Fig. 6).

Clinical Outcome

A total of 12 TTSs and 12 OSSs were successfully implanted in the S2 and S1 segments, respectively, with the assistance of navigation templates, and the screws were in good position (Fig. 7A–F). With a surgical time of 55 ± 7.69 min, bleeding of 57.5 ± 18.15 ml and radiation of 14.5 ± 4.95 times, one of the TTS and one of the OSS were evaluated as grade 1, and the other screws were evaluated as grade 0. The Matta scores of nine patients were excellent, and those of three patents were good (Table 2).

Discussion

In our study, six FEA models of the pelvis were conducted and analyzed for comparative study. The displacement results showed that the S1 + S2 screw placement had better fixation strength than one S2 screw, which was close to the normal pelvis. The S1 OSS + S2 TTS had the best fixation strength with a relatively low stress concentration effect. Based on these results, we conclude that this is the best fixation method for sacroiliac dislocation in dysplastic sacrum. Clinically, a total of 12 TTSs and 12 OSSs were successfully implanted with the assistance of locked navigation templates, and 92%of the screws were completely inside the corridors, which means that the majority of the screws were in a good position. The Matta scores were excellent in nine patients and good in three patients, which means all the patients recovered well. The results of this study indicate that it is safe for sacroiliac screw insertion assisted by locked navigation templates.

FEA of Screw Fixation for Sacrum Dysplasia

Sacroiliac screws and plate screws are often used to treat posterior pelvic ring instability. Sacroiliac screws can solve most of the instability issues of the posterior pelvic ring, and OSS has been widely used in the operating room.[13,14] However, it is difficult to find a stabilizing device to control the angle of OSS, and it is difficult to ensure patient safety through intraoperative X-ray. Therefore, TSSs are favored because of their superior mechanical properties;[15] additionally, they can be easily identified by intraoperative fluoroscopy at the inlet and outlet of the pelvis or the lateral position of the sacrum.

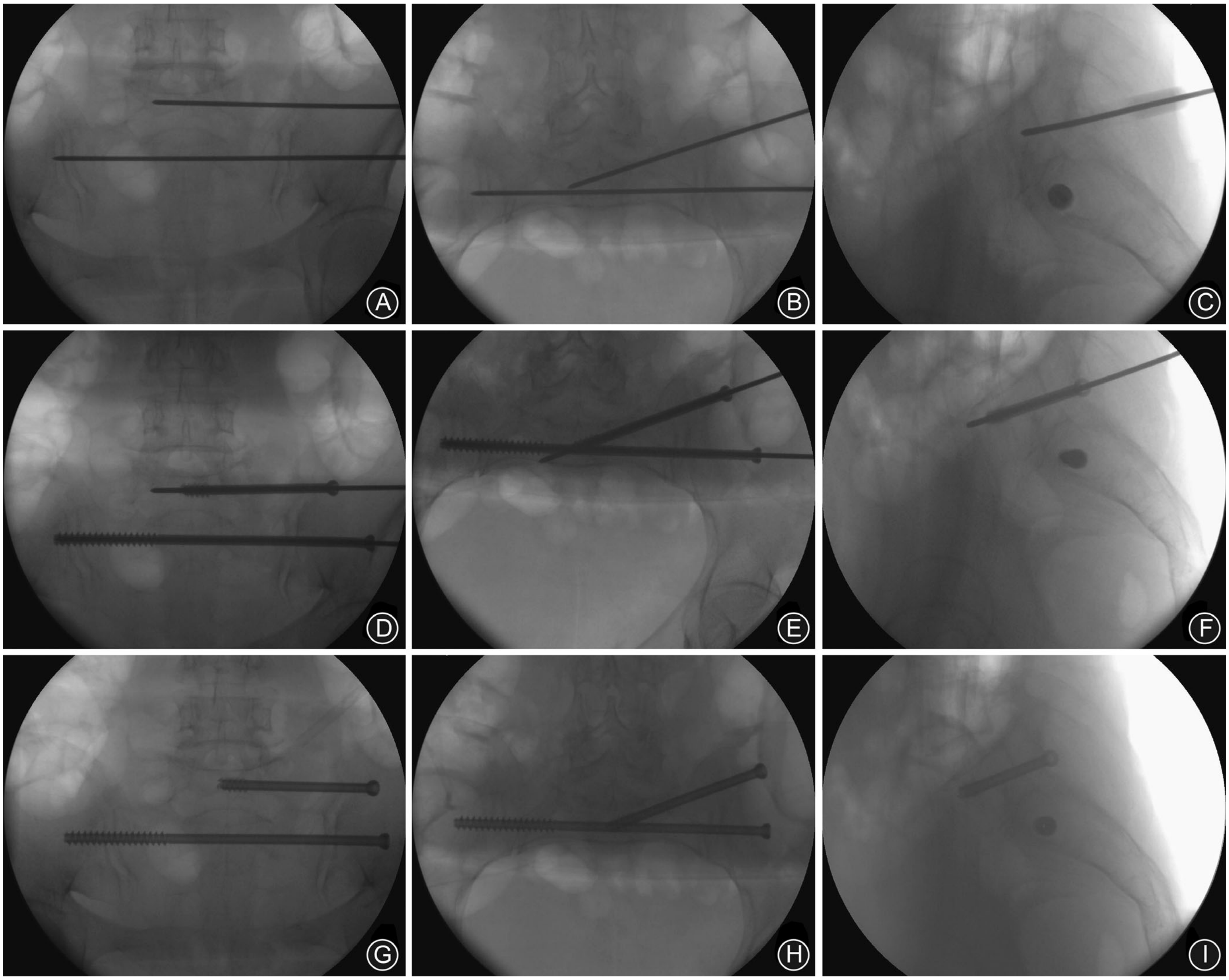

Fig. 5 Intraoperative C-arm fluoroscopy of the above patients (A-I). Intraoperative C-arm fluoroscopy in inlet (B, E, H), outlet (A, D, G) and lateral (C, F, I) showed that the Kirschner wire and screw were in good position with no breakthrough of cortical bone.

TABLE 3 Maximum stress and vertical displacement of sacrum surface in FE model

Fixation method	Maximum stress	VDS (mm)
S2OSS	139.45	1.2364
S2TSS	144.81	1.4235
S2TTS	126.14	1.2212
S1OSS + S2OOS	149.26	0.91318
S1OSS + S2TSS	167.13	1.0609
S1OSS + S2TTS	136.76	0.75779
Normal		1.0369

However, TSS or TTS cannot be accommodated in the S1 segment for patients with very high oblique sacral wings.[16–21] –21 For these patients, we inserted an OSS in the S1 segment combined with a TTS in the S2 segment; whether this is the best method of internal fixation is an urgent question. Due to the scarcity of cadavers, FEA has become the preferred method of mechanical analysis in orthopedic internal fixation research.

In a previous study, FEA was used in different types of sacroiliac screw implantation, and some research indicated that TTS had better mechanical stability.[22,23] However, few studies have conducted FEA of screw fixation in sacral variation. In this study, we used finite element analysis to explore the best sacroiliac screw internal fixation combination for pelvic fractures of the dysplastic sacra. For a better simulation, the fine-cut CT data were obtained and used to establish the FE model. The assignment of model materials and construction of ligaments were performed according to previous studies.[24] The results showed that the upper surface displacement of the sacrum in the intact model was close to the result of a

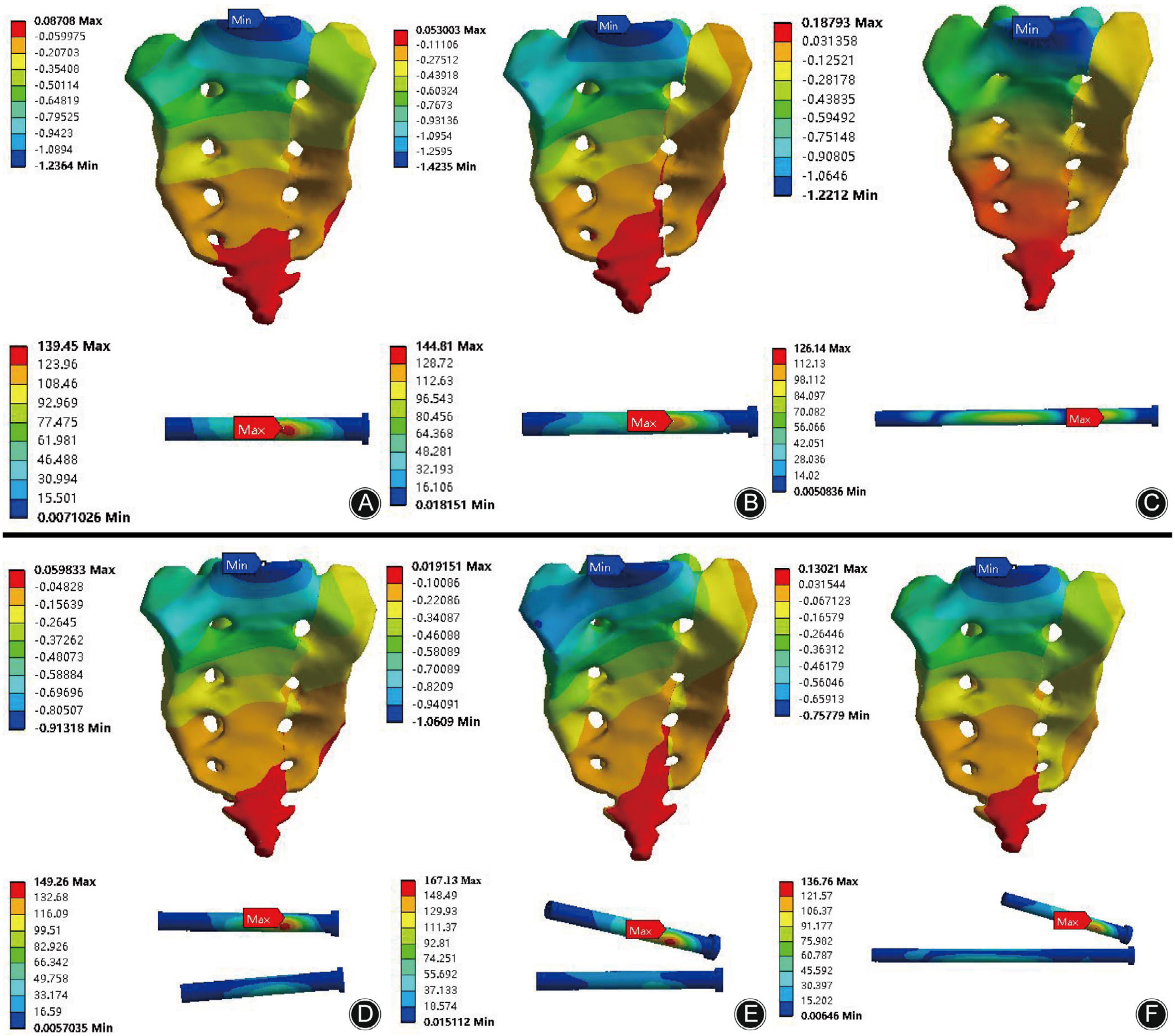

Fig. 6 The results of displacement and stress of S2 OSS (A), S2 TSS (B), S2 TTS (C), S1 OSS + S2 OSS (D), S1 OSS + S2 TSS (E) and S1 OSS + S2 TTS (F). The vertical downward displacement of the S1 upper surface in each model (up), the negative number represent downward displacement. The Von Mises stress of the screw (down) show where the internal fixation failure is most likely to occur.

previous study,[14] indicating that this model could simulate mechanical loading and be used for the next analysis.

The displacement results showed that the S1 OSS + S2 TTS had the lowest value among the six fixation methods, indicating that it had the strongest fixation strength. In the one-screw fixation group, the fixation strength of S2 OSS was higher than that of S2 TSS. This may be because the screw direction was perpendicular to the fracture surface. This phenomenon also occurred in the two-screw fixation group, indicating that the OSS has better biomechanical properties than TSS in the fixation of pelvic vertical instability fractures.

The stress distribution map showed that the maximum stress of the implant in the S2 TTS was the lowest, followed closely by the S1 OSS + S2 TTS. Overall, the S1 OSS + S2 TTS was the best fixation choice for the pelvic vertical instability model.

Advantages of Transiliac-Transsacral Screws

The patients in our research had an average surgical time of 55 min, blood loss of 57.5 ml and radiation of 14.5 times, which were significantly less than those of conventional pelvic fixation, robot navigation and computer navigation.[25–28] The reasons are as follows: first, the navigation template base

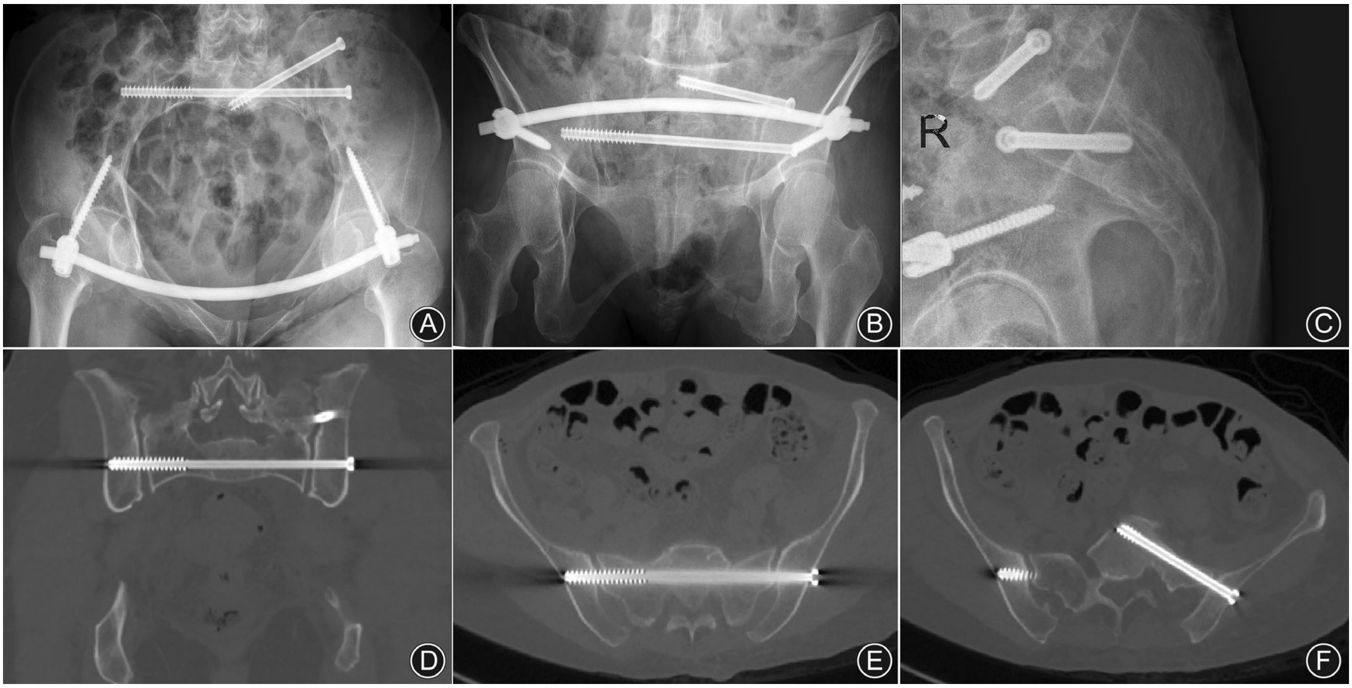

Fig. 7 Postoperative images of the above patients. (A–C) Postoperative, the x-rays in inlet view, outlet view and lateral view. (D) Transiliac-transsacral screw in the S2 segment in the coronary position. (E) Transiliac-transsacral screw in the S2 segment in the axial position. (F) Oblique sacroiliac screw in the S1 segment in the axial position.

was designed based on the posterior superior iliac spine and has obvious anatomical marks, so screw insertion safety was guaranteed. Second, some holes were designed on the navigation template base to insert screws that fix the navigation template and bone so that the navigation template and bone surface were stably attached. Third, in this study, the navigation template base and the navigation tube were combined in design. During the operation, the base and the navigation tube were inserted separately and then combined through threads, which greatly reduced the incision length and blood loss. Fourth, the inner diameter of the navigation hole on the base was greater than 9 mm, so the screw could be implanted along the Kirschner wire, and then the base could be removed, which greatly improved the surgical efficiency. This technique was demonstrated to be safe and reliable based on our clinical observations and surgical verification.

Surgery Tips

For a better application for navigation template, we suggest the following surgical tips: first, the operation process was simulated based on a 3D-printed pelvis to verify the safety of the screw placement; second, preoperative fluoroscopy confirmed the overlap point of the screw inlet on the skin to reduce incision size and reduced skin and soft tissue interference with guide tube; third, patients were placed in the standard prone position; fourth, the template base was combined with the bone by a 2.5 mm diameter screw; fifth, intraoperative x-ray was recommended to verify the security of screws by inlet, outlet and lateral sacrum positions.

Limitations

Because FEA is an idealized computational approach for *in vitro* calculations, the actual operation and clinical conditions are not completely consistent, and further clinical validation is essential. The long-term follow-up of surgical patients is lacking in this study.

Conclusion

FEA showed that for patients with sacrum dysplasia, the insertion of an oblique sacroiliac screw in S1 combined with a transiliac-transsacral screw in the S2 segment had the best mechanical stability. Sacroiliac screw placement with patient-specific locked navigation template assistance is clinically safe.

Author Contributions

Chao Wu was responsible for the experimental design and paper review; Baifang Zeng for data analysis and paper writing; Jiayan Deng and Binwei Qin for paper writing; Danwei Shen for data preprocessing; Xiangyu Wang,

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