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Original Article

Biomechanical evaluation of percutaneous anterograde and retrograde screw implantation for superior ramus pubis fractures: a finite element analysis

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Abstract: Objective: To evaluate the biomechanical characteristics of percutaneous anterograde and retrograde screw implantation for superior ramus pubis fractures. Methods: Mimics software was used to reconstruct the normal pelvis. 3-Matic software was used to establish a model for superior ramus pubis fracture, and percutaneous anterograde/retrograde screw implantation was used to simulate the treatment of a superior ramus pubis fracture. After material assignment by Mimics software, Ansys software simulated the force of a standing position with a 600 N load on an S1 vertebral endplate and then compared the mechanical stability. Results: After simulating the fracture at five points, the effect of anterograde and retrograde screw implantation on the displacement and stress of the pelvis and the left pubic bone were found to be similar. When anterograde screw implantation was used, screw displacement at each point was 1.10 mm, 1.04 mm, 1.10 mm, 1.10 mm, and 1.07 mm; the stress at each point was 14.95 MPa, 11.50 MPa, 18.60 MPa, 18.07 MPa, and 18.37 MPa. When retrograde screw implantation was used, screw displacement at each point was 0.62 mm, 0.62 mm, 0.70 mm, 0.76 mm, and 0.87 mm; and the stress at each point was 5.13 MPa, 4.03 MPa, 6.61 MPa, 9.74 MPa, and 11.55 MPa respectively. Conclusions: When assessing the treatment of superior ramus pubis fractures from a biomechanical perspective, we found that if the distance between the fracture line and the insertion point is less than 70 mm, it is recommended to use retrograde screw implantation.

Keywords: Anterograde screw implantation, retrograde screw implantation, superior ramus pubis fractures, finite element analysis

Introduction

Most pelvic fractures are caused by car accidents, high falls, and other physical traumas, which often destroy the structural integrity of the anterior and posterior pelvic rings and are considered one of the more serious orthopedic injuries [1, 2]. In the past, the most common treatment of pelvic fractures has been to fix the posterior ring of the pelvis, however, as biomechanical research has improved, scientists have begun to realize that restoring the integrity of the pelvis involves not only restoring the continuity and stability of the posterior ring structure of the pelvis, but also restoring the stability of the anterior ring structure of the pelvis [3]. Pubic ramus fracture is a common type of anterior pelvic ring injury. Biomechanical studies have shown that fixation of a pubic ramus fracture can not only reduce the stress level of the posterior pelvic ring fixation system, but also benefit the stability of the pelvic ring structure [4].

Currently, the fixation methods for anterior pelvic ring injury include anterior subcutaneous

Table 1. Finite element model and material properties of internal fixation

Material	Elastic modulus, E (MPa)	Poisson ratio, μ	Stiffness Coefficient
Cortical bone	17000	0.30	-
Cancellous bone	132	0.20	-
Sacral bone	6140	0.30	-
Femur	18200	0.38	-
Cartilago articularis	54	0.40	-
Acetabulum cartilage	12	0.42	-
Symphysis pubis	5	0.45	-
Sacrospinous ligament	-	-	1400
Ligamentum sacrotuberale	-	-	1500
Superior pubic ligament	-	-	500
Arcuate pubic ligament	-	-	500
Screw (titanium alloy)	114000	0.30	-

fixation, external fixation, plate internal fixation, and percutaneous screw internal fixation [5]. Each surgical procedure has its own advantages and disadvantages. As a minimally invasive technique, percutaneous screw fixation has been gradually applied in the treatment of anterior ring fractures of the pelvis in recent years due to causing less soft tissue damage and less intraoperative blood loss [6-8]. As early as 1995, Routt proposed percutaneous screw fixation of the pubic ramus, which was subsequently widely used in clinical practice [9]. Screw implantation can be further divided based on whether there is forward screw fixation or reverse screw fixation [10]. There is no consensus as to which fixation direction is better. In this study, the biomechanical characteristics of percutaneous anterograde and retrograde screw implantation in the treatment of superior ramus pubis fractures were evaluated by finite element analysis, which provided a theoretical basis for the selection of screw implantation direction for clinical treatment of such fractures.

Materials and methods

Design

Finite element analysis experiment.

Materials

A healthy male volunteer, aged 28, 170 cm in height and 70 kg in weight, was selected as the observation subject.

Inclusion and exclusion criteria: 1) The volunteers could complete relevant imaging examination in accordance with the doctor's advice; 2) Exclude bone destruction associated with a tumor, deformity, osteoporosis patients, suprapubic stenosis patients, comminuted fracture patients, obese patients and pathological fracture; 3) Pelvic data were obtained by Computed Tomography (CT) scan; 4) Sign the relevant informed consent.

Instruments: 64-slice spiral CT (Siemens, Germany), Mimics 20.0 (Materialise, Belgium), 3-Matic 12.0 (Materialise, Belgium), Ansys 19.2 (Ansys, USA).

Methods

Data collection: A 64-slice spiral CT was used to scan the pelvis of the volunteer. The scanning conditions were 140 kV, 200 mA, and the thickness was 0.625 mm. CT data were extracted in 512×512 pixel DICOM format [11].

Establishment of a three-dimensional model of the pelvis: The CT data from the volunteer was imported into Mimics 20.0 software to conduct three-dimensional reconstruction of the pelvis and establish a geometric model of the whole pelvis, which was imported into 3-Matic 12.0 software in Standard Template Library (STL) format [12]. The tools included in the software, including mesh diagnosis and surface parameter fitting, were used to divide the surface mesh and volume mesh of the pelvis [13] and generate a three-dimensional model of the physical pelvis.

Establishment of a finite element model of the pelvis: The three dimensional model of the materialized pelvis was imported into Ansys 19.2 software to set material properties and establish a complete finite element model of the pelvis. Material assignment was performed using Mimics 20.0 software. The specific material parameters [14-17] are shown in **Table 1**.

Validation of the finite element model: We verified whether anatomical and morphological dif-

Table 2. Marking points and explanation of the model of percutaneous anterograde and retrograde screw implantation for superior ramus pubis fractures

Marking points	Explanation
Point M	Entry point of percutaneous retrograde screw implantation
Point N	Entry point of percutaneous anterograde screw implantation
Point A	Point B extends outward 10 mm, and the distance of AN is 80 mm
Point B	The point through which the fracture line passes, BN distance is 70 mm
Point C	The midpoint of BD, BD distance is 15 mm
Point D	The point through which the fracture line passes, MD distance is 70 mm
Point E	Point D extends outward 10 mm, and the distance of ME is 80 mm
MN	Maximum length of the entire nail track, 127 mm
MP	Length of percutaneous retrograde screw implantation, 100 mm
ON	Length of percutaneous anterograde screw implantation, 100 mm

ferences existed [18, 19] by measuring the distance between the three-dimensional pelvic model and the finite element model at each marker point and comparing the measurements. The relevant markers include: 1) ipsilateral hip anterior superior iliac spine to posterior superior iliac spine; 2) the anterior superior iliac spine to the highest point of the greater sciatic notch; 3) the highest point of iliac crest and ischial tuberosity; 4) ischial tubercle to ipsilateral pubic tubercle; 5) the maximum longitudinal length of the acetabular fossa; 6) the maximum axial length of the acetabular fossa; 7) promontory of sacrum to anterior inferior iliac spine; 8) between the upper edge of bilateral sacroiliac joints; 9) S1 Anterior and posterior central margins of the vertebral body.

Establishment of the finite element model of percutaneous anterograde or retrograde screw implantation for the treatment of superior ramus pubis fractures: The entry point of the retrograde screw implantation (M point) was selected below the midpoint of the pubic crest (7.5±0.5) mm [20], and a smooth cylinder, which was used to mimic the effect of a screw, was implanted into the left superior ramus of the pubic bone. The screw passed through the pubic channel from below the midpoint of the left pubic crest to the left iliac cortical bone, and the distance between the two (MN) is the maximum length of the entire screw passage (127 mm), and the point where the screw passes out of the left iliac cortical bone along the pubic passage is the entry point (N).

Previous literature has shown that longer screws can provide better stability, but too long (length > 100 mm) and too thin (diameter < 6.5 mm) screws significantly increase the risk of fracture. Therefore, the screw diameter in this study was set to 6.5 mm [21], and the screw length was dependent on the specific situation. Combined with previous literature studies and clinical experience, the maximum screw length was not to exceed 110 mm.

It was assumed that the left superior ramus of the pubis was implanted with percutaneous anterograde or retrograde screw, and the same screw channel was used for both implants. The screw length (Retrograde screw implantation: MP; Anterograde screw implantation: ON) was set to 100 mm, and the screw length was defined as more than 30 mm across the fracture line. Then, the distance from the entry point to the fracture line (Retrograde screw implantation: MD; Anterograde screw implantation: BN) was 70 mm; Point B and point D are the points through which the fracture line passes. The area between B and D is the boundary area where both the forward and reverse screws can be implanted. B and D are divided into two equal parts, and the midpoint is point C. According to clinical experience, the maximum length of the screw should not be more than 110 mm. Therefore, the distance from the entry point to the fracture line was 80 mm, and the points B and D extend outward 10 mm respectively, namely points A and E. The distance between ME (Retrograde screw implantation) and AN (Anterograde screw implantation) was 80 mm and are shown in **Table 2**. The 3-Matic 12.0 software was used to divide A fracture line perpendicular to the screw channel at five points (A, B, C, D, and E) and simulate

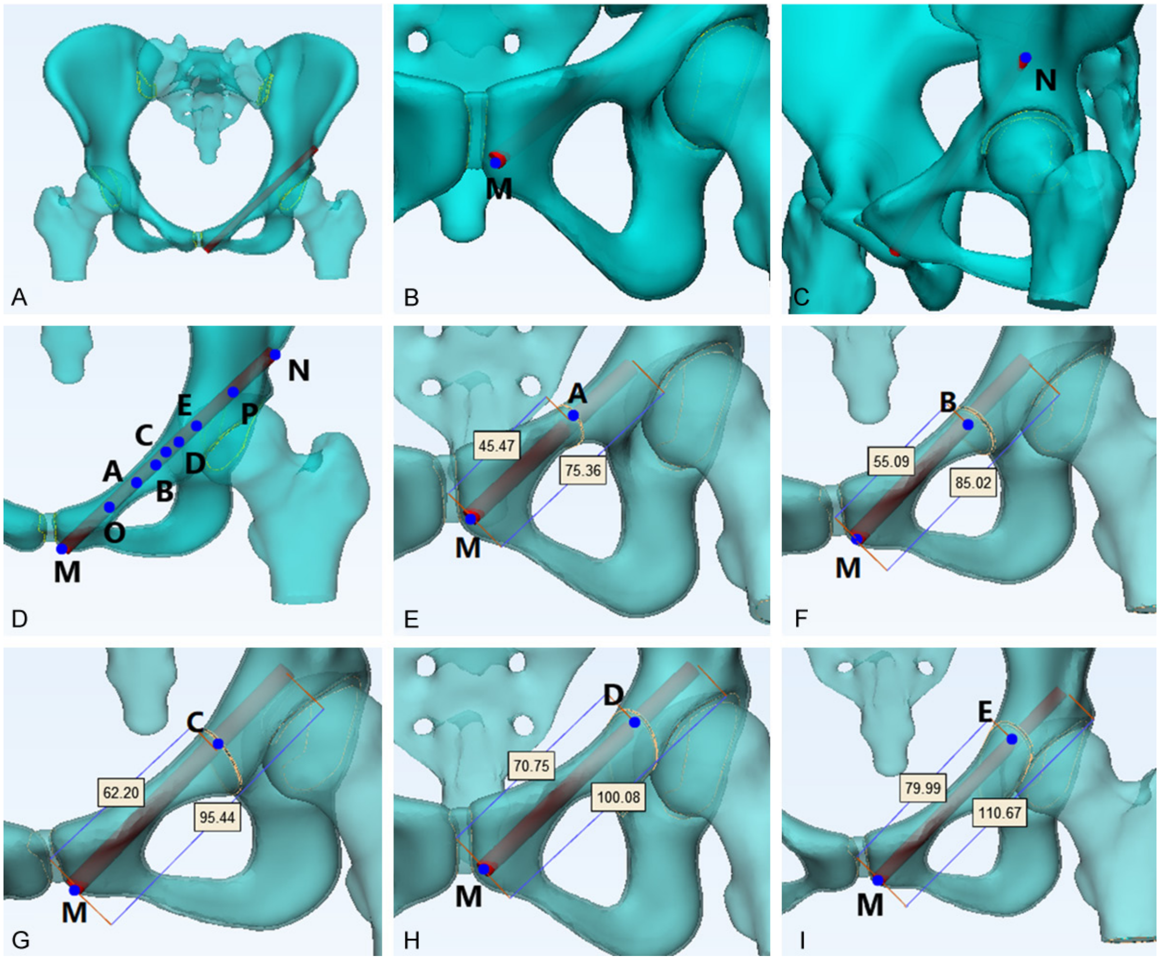

Figure 1. The establishment process of three dimensional model for screw simulation treatment of superior ramus pubis fracture. Figure note: (A-D) screws were used to simulate the treatment of superior ramus pubis fracture. Long red cylinder screws were used to simulate the treatment. See **Table 2** for the explanation of each marker point. (E-I) divided the fracture line at points A, B, C, D and E. Taking the superior ramus of the pubis as an example, the process of screw implantation after fracture was simulated at five points, and the distance from the insertion point to the fracture line and the length of the corresponding screw were marked. (E) The distance (MA) from the entry point to the fracture line is 45 mm, and the screw length is 75 mm; (F) The distance (MB) from the entry point to the fracture line is 55 mm, and the screw length is 85 mm; (G) The distance (MC) from the entry point to the fracture line is 62.5 mm, and the screw length is 95 mm; (H) The distance (MD) from the entry point to the fracture line is 70 mm, and the screw length is 100 mm; (I) The distance (ME) from the entry point to the fracture line is 80 mm, and the screw length is 110 mm.

the fracture of the left superior ramus of the pubis in the corresponding area as shown in **Figure 1**.

The finite element model of percutaneous anterograde or retrograde screw implantation in the treatment of superior ramus pubis fractures was established according to the above steps. Assigning material, and making binding contacts between bone and articular cartilage. The S1 vertebral endplate was selected as the loading surface, a 600 N load was applied vertically downward, and the cross sections of the lower ends of both femurs were selected as a fixed surface to limit their degrees of freedom in six directions, so as to simulate the stress state of the human body in a standing position.

Observational index

1) Results of finite element analysis of volunteer's normal pelvis; 2) Finite element analysis of displacement and stress of percutaneous anterograde or retrograde screw implantation for superior ramus pubis fractures.

Table 3. Comparison of the distance between three-dimensional pelvic model (TDM) and the finite element model (FEM) (mm)

Model	①	②	③	④	⑤	⑥	⑦	⑧	⑨
TDM	144.75	97.72	176.66	110.53	53.80	57.26	115.83	116.24	28.76
FEM	145.63	98.64	177.91	111.27	54.67	58.44	116.79	117.58	28.93

Table 4. The effect of screw simulation on the displacement and stress of a pelvis with superior pubic ramus fracture

Catalogue	Displacement (mm)		Stress (MPa)	
	Anterograde	Retrograde	Anterograde	Retrograde
Point A	2.90	2.91	31.53	31.63
Point B	2.89	2.88	31.45	31.63
Point C	2.88	2.88	31.69	31.92
Point D	2.89	2.88	40.23	39.75
Point E	2.89	2.89	40.35	40.10

Table 5. The effect of screw simulation on the displacement and stress of the left pubic bone with a superior pubic ramus fracture

Catalogue	Displacement (mm)		Stress (MPa)	
	Anterograde	Retrograde	Anterograde	Retrograde
Point A	2.81	2.83	21.33	21.41
Point B	2.79	2.81	21.01	22.03
Point C	2.82	2.82	21.55	21.94
Point D	2.82	2.83	23.20	22.59
Point E	2.83	2.83	21.68	21.62

Table 6. The effect of screw simulation on the displacement and stress of the screw with superior pubic ramus fracture

Catalogue	Displacement (mm)		Stress (MPa)	
	Anterograde	Retrograde	Anterograde	Retrograde
Point A	1.10	0.62	14.95	5.13
Point B	1.04	0.62	11.50	4.03
Point C	1.10	0.70	18.60	6.61
Point D	1.10	0.76	18.07	9.74
Point E	1.07	0.87	18.37	11.55

Results

Validation results of the finite element model

Table 3 is the comparison of the distance between the three-dimensional pelvic model and the finite element model. We found little difference in the distance between the three-dimensional pelvic model and the finite element pelvic model. The finite element model established in the early stage of the study is effective.

Finite element analysis

Finite element analysis of the pelvis: **Table 4** shows the effect of screw simulation on the displacement and stress of a pelvis with superior pubic ramus fracture. As indicated in **Table 4**, after the superior ramus pubis fracture was simulated at points A, B, C, D, and E, the displacement changes and stress changes of each pelvic model were equivalent, whether they received percutaneous anterograde or retrograde screw implantation.

Finite element analysis of the left pubic bone: **Table 5** shows the effect of screw simulation on the displacement and stress of the left pubic bone with a superior pubic ramus fracture. As seen in **Table 5**, after the superior ramus pubis fracture was simulated at points A, B, C, D, and E, the displacement changes and stress changes of each left pubis model were equivalent, whether they recieved percutaneous anterograde or retrograde screw implantation.

Finite element analysis of the screw: **Table 6** shows the effect of screw simulation on the displacement and stress of the screw with superior pubic ramus fracture. As shown in **Table 6**, after the superior ramus pubis fracture was simulated at points A, B, C, D, and E, the displacement of the screw was higher in anterograde screw implantation compared to retrograde screw implantation. When retrograde screw implantation was used, the displacement of the screw from point A to point E showed a trend of increasing gradually. When the anterograde screw implantation was used, the stress of the screw itself was higher than the retrograde screw implantation. The stress of the screw from point A to point E increased

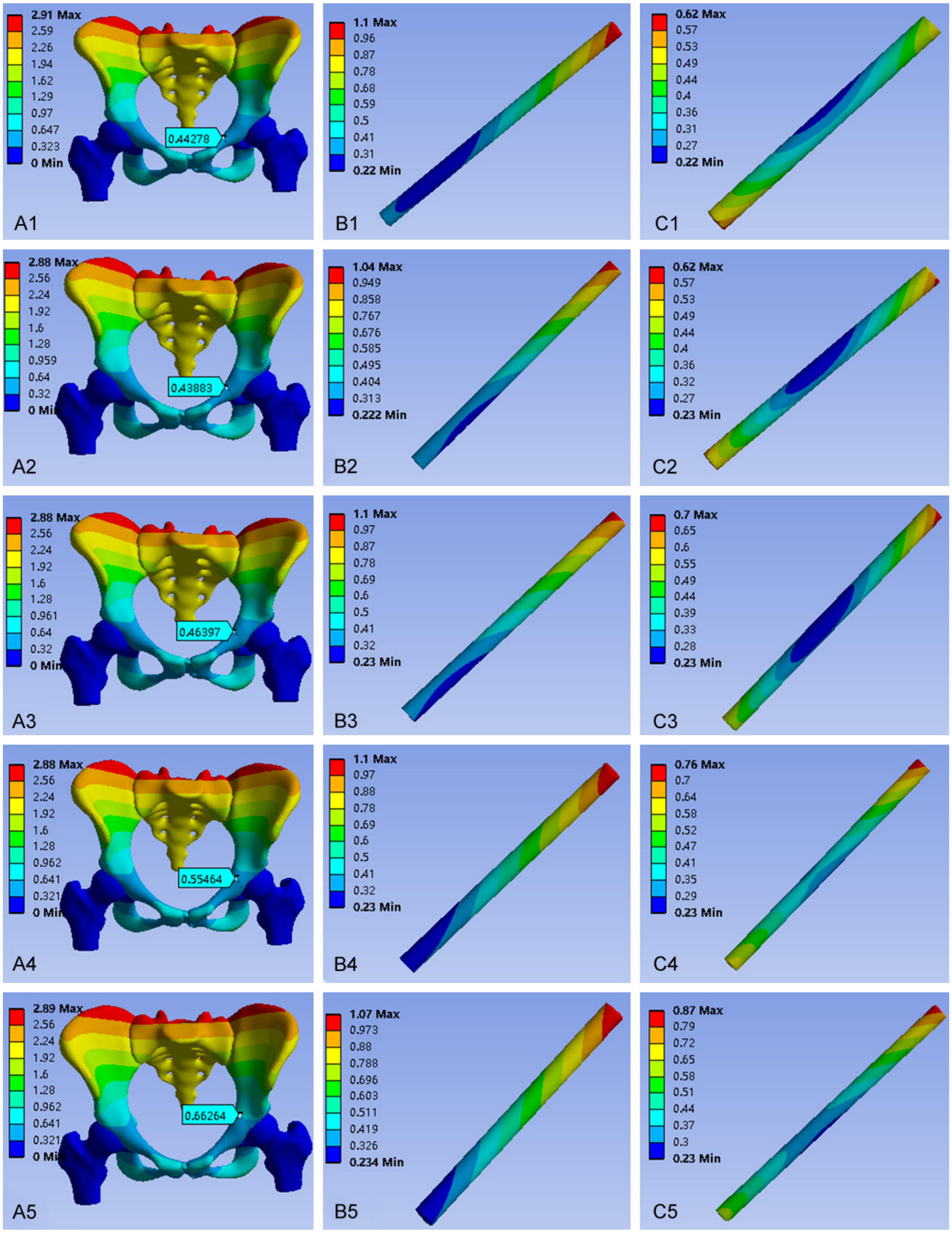

Figure 2. Displacement distribution of screw and five marks. Figure note: (A1-A5) After simulating superior ramus pubis fracture, the displacement distribution results at five marker points (A, B, C, D and E) were 0.44 mm, 0.44 mm, 0.46 mm, 0.55 mm and 0.66 mm. (B1-B5) Percutaneous anterograde screw implantation for superior ramus pubis fractures, the displacement distribution results at five points; (C1-C5) Percutaneous retrograde screw implantation for superior ramus pubis fractures, the displacement distribution results at five points.

gradually when the screw was implanted in both directions. The displacement and stress distribution of the screw across the five marker points are shown in **Figures 2** and **3**.

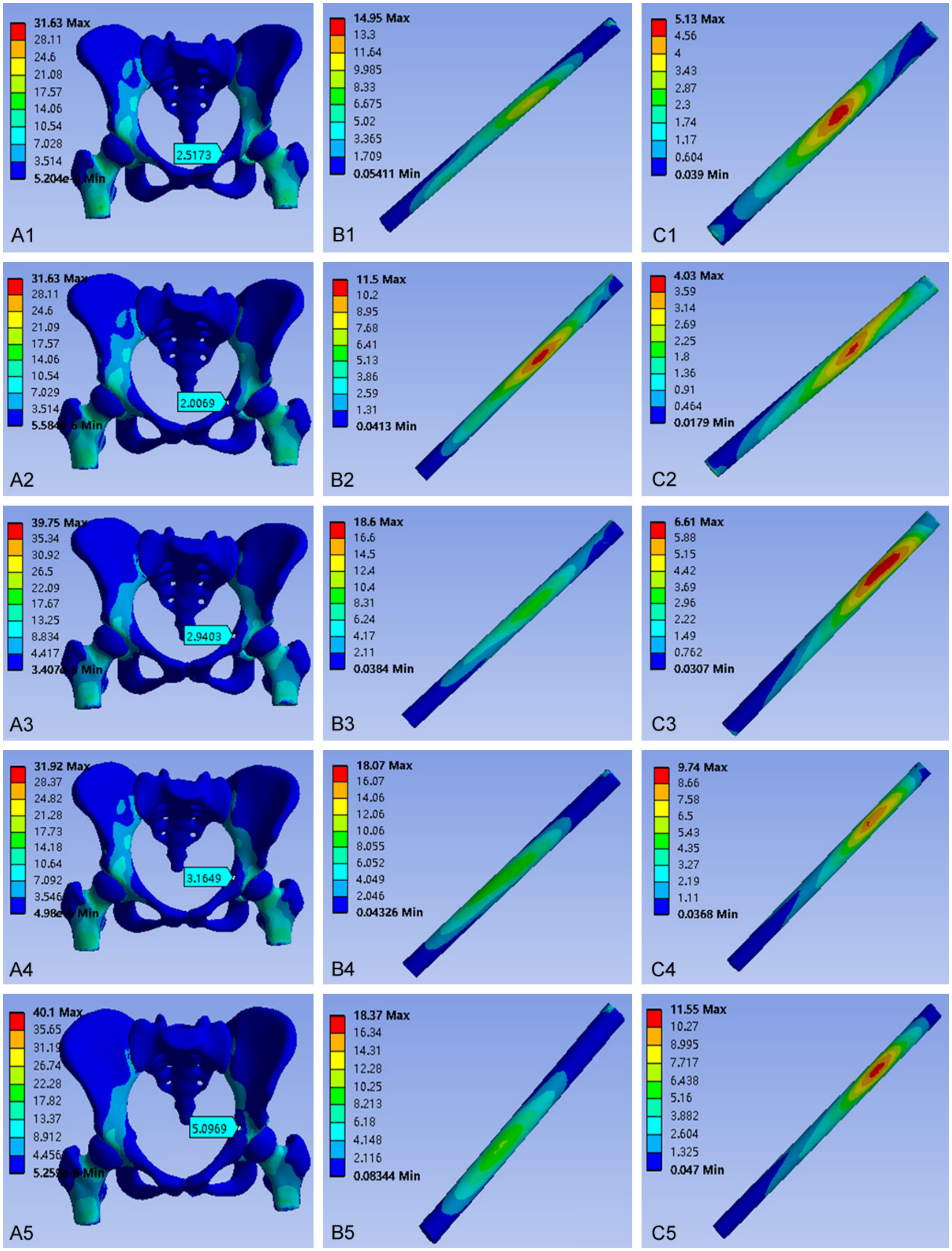

Figure 3. Stress distribution of screw and five marks. Figure note: (A1-A5) After simulating superior ramus pubis fracture, the stress distribution results at five marker points (A, B, C, D and E) were 0.44 mm, 0.44 mm, 0.46 mm, 0.55 mm and 0.66 mm. (B1-B5) Percutaneous anterograde screw implantation for superior ramus pubis fractures, the stress distribution results at five points; (C1-C5) Percutaneous retrograde screw implantation for superior ramus pubis fractures, the stress distribution results at five points.

Discussion

Analysis of the results

We have shown that after the superior ramus pubis fracture was simulated at points A, B, C, D, and E, the displacement changes and stress changes of each pelvic model were equivalent, whether they received percutaneous anterograde or retrograde screw implantation. After the superior ramus pubis fracture was simulated at above fivepoints, the displacement changes and stress changes of each left pubis model were equivalent, whether they received percutaneous anterograde or retrograde screw implantation. We also found that when anterograde screw implantation was used, the displacement and stress of the screw itself was higher than that of retrograde screw implantation, indicating that the screw will undergo greater deformation and bear greater stress when anterograde screw implantation is used. Under the same loading conditions, the screw is more prone to fracture. Therefore, from a biomechanical point of view, when a fracture occurs at any one of the five points assessed in this study, the safety of retrograde screw implantation is better than that of anterograde screw implantation.

At the same time, the displacement and stress of the screw from point A to point E gradually increased when retrograde screw implantation was used. We also found that displacement and stress at the five marker points increased gradually after the fracture was simulated. This could explain why the displacement and stress of the screw from point A to point E gradually increased when the retrograde screw implantation was used.

Analysis of the reasons for choosing the retrograde screw implantation

When retrograde screw implantation was used, the longer the length of the screw, the more likely it is to break. This risk, however, was not seen in association with anterograde screw implantation. We further analyze the reasons: 1) There are differences between displacement and stress at the five marked points, and displacement and stress gradually increase from point A to point E. 2) The closer you get to point E, the closer you get to the major stress bearing area of the pelvis. Therefore, with the increase of the length of the retrograde implanted screw, the screw gradually approached the main stress-bearing area of the pelvis, and displacement and stress increased accordingly. When using anterograde screw implantation, the screw must pass through the primary stress bearing area of the pelvis in the beginning, so, in this instance, displacement and stress associated with the screw are higher than that of retrograde screw implantation. With an increase in the length of the anterograde implanted screw, displacement and stress of the screw will also gradually increase. The increase in the length of the screw also increased the area where the screw bears stress, thus increasing the total stress on the screw. It is important to note that it is not that the longer the screw length, the greater the stress; considerations must also be made in conjunction with the fracture site.

In the case of a superior ramus pubis fracture, it is recommended to choose retrograde screw implantation on the premise that the fracture line does not exceed point D, that is, the distance between the fracture line and the entry point is not more than 70 mm, and the screw length is not more than 100 mm, which is consistent with the conclusion of Suzuki [21]. Longer screws can provide better stability, but screws that are too long (length > 100 mm) and too thin (diameter < 6.5 mm) significantly increase the risk of fracture. We analyzed the reasons for choosing retrograde screw implantation because, compared with retrograde screw implantation, the anterograde screw implantation requires longer screws, which would bring new problems, including: 1) With an increase in the length of the screw, the stress on the screw will increase, and result in greater risk of fracture; 2) An increase in screw length will increase the number of scanning and difficulty of intraoperative radiographs; 3) An increase in screw length will also have a certain impact on the operation. Firstly, the operation will be more difficult to perform because of the risk of the screw breaking through cortical bone due to the increased screw length. The second is the increase in surgical time. Due to these issues, we recommend using retrograde screw implantation. Of course, the length of the screw can also be appropriately increased, but it should be noted that with the increase in screw length, the stress on the screw itself will increase, that is, the screw is more prone to fracture.

Limitations in this research

This study also has limitations [22]: 1) The structure of the pelvis was not completely simulated, but only the bony structure, major ligaments, and cartilage of the pelvis were simulated; 2) There is no real simulation of the physiological state of the human body, only the standing state of the human body is simulated; 3) The screw is simplified and the long cylinder is used to simulate the screw, but the screw thread is not simulated; 4) The model was only based off a male pelvis, and there can be significant different between the pelvises of males and females. Despite these shortcomings, our study can provide references for other researchers and a theoretical basis for clinical work.

Conclusions

When treating superior ramus pubis fractures from a biomechanical perspective, we recommend choosing retrograde screw implantation when the distance between the fracture line and the insertion point is less than 70 mm. Of course, the choice of specific surgical methods must be combined with the actual clinical situations because the difficulty of a surgical operation, surgical experience of the surgical team, etc., will affect the ultimate outcomes of surgery.

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Disclosure of conflict of interest

None.

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