Mechanical comparison between lengthened and short sacroiliac screws in sacral fracture fixation: A finite element analysis

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KEYWORDS
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Pelvic ring disruption

Summary
\textbf{Objective}: To compare the stability of lengthened sacroiliac screw and standard sacroiliac screw for the treatment of unilateral vertical sacral fractures; to provide reference for clinical applications.

\textbf{Methods}: A finite element model of Tile type C pelvic ring injury (unilateral Denis type II fracture of the sacrum) was produced. The unilateral sacral fractures were fixed with lengthened sacroiliac screw and sacroiliac screw in six different types of models respectively. The translation and angle displacement of the superior surface of the sacrum (in standing position on both feet) were measured and compared.

\textbf{Results}: The stability of one lengthened sacroiliac screw fixation in S1 or S2 segment is superior to that of one sacroiliac screw fixation in the same sacral segment. The stability of one lengthened sacroiliac screw fixation in S1 and S2 segments respectively is superior to that of one sacroiliac screw fixation in S1 and S2 segments respectively. The stability of one lengthened sacroiliac screw fixation in S1 and S2 segments respectively is superior to that of one lengthened sacroiliac screw fixation in S1 or S2 segment. The stability of one sacroiliac screw fixation in S1 and S2 segments respectively is markedly superior to that of one sacroiliac screw fixation in S1 or S2 segment. The vertical and rotational stability of lengthened sacroiliac screw fixation and sacroiliac screw fixation in S2 is superior to that of S1.

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Sacroiliac screw has become a common technology in fixing pelvic posterior ring injuries, and it is also used in sacroiliac joint tumors and sacral insufficient fractures, etc. Appearance of lengthened sacroiliac screw, in theory, brought new minimally invasive treatment options for bilateral sacroiliac joints injury, bilateral sacral fractures and those combining osteoporosis, and made it possible to decrease fixation failure rate of unilateral sacral fracture and dislocation. But related reports were rarely seen, and were limited to clinical application research of small sample size [1,2]. So far, there is almost no related basic research for the lengthened sacroiliac screw technique and as for what kind of sacroiliac screw or its combination provides more stable fixation, there is no related basic reports to check. In this study we used three-dimensional finite element technique to imitate two kinds of sacroiliac screws (lengthened sacroiliac screw and sacroiliac screw) fixation in unilateral vertical sacral fractures (Tile C) to compare their stability and provide reference for clinic application.

Methods

A finite element pelvis model was biomechanically evaluated in intact condition and following successions. Load of 600N was imposed on the scum and the stress of pelvis, downward translation and backward angle displacement of middle part of sacral superior surface and stress of fixation system were extracted for analysis. The material properties and elements used in the models are available in Tables 1 and 2 [3–5].

In order to define the solid geometry of the pelvic bones, an anatomic pelvic model from CT data of a healthy woman (36 years old, 170 cm, 63 kg) was constructed. A 64-slice spiral CT (Philips) was used to obtain images of pelvis with a scan thickness of 1 mm. The CT data was imported into medical software (mimics 10.0) to construct the 3D surface mesh of sacrum and innominatum. The surface mesh was used as the basis for defining the geometric extents of cortical and trabecular bone of the pelvis. Four nodded linear solid tetrahedral elements with an average edge length of 2 mm were used in Abaqus/CAE to create an unstructured mesh of the trabecular bone. Triangle shell elements with a thickness of 2 mm were used to represent the cortical bone, surrounding the trabecular bone [3]. Tied conditions were assumed between the internal surface of the cortical bone and the surface of the trabecular bone. Young’s modulus and Poisson’s ratio were taken to be 150 N/mm² and 0.2 for trabecular bone, and 18,000 N/mm² and 0.3 for cortical bone [3]. The sacroiliac cartilage and interpubic disc were represented as continuum structure occupying the inter-space and mesh into hexahedron element. Because of their important roles in pelvic biomechanics and stability, sacroiliac ligament, sacrospinous ligament and saerotuberous ligament, etc. were incorporated and modeled as tension-only discrete axial connectors. The attachment points were ascertained by being mimesised anatomy as closely as possible. The final finite element normal pelvis was printed in Fig. 1.

The sacrum was cut into two parts through right sacral foramen to develop the model of unilateral sacral fracture. In the simulation, two kinds of cannulated screws (lengthened sacroiliac screw and sacroiliac screw) with a diameter of 7.3-mm were used to be placed at S1 or S2 or both of S1 and S2 in the models of unilateral sacral fracture.

Six fixation cases were imitated for finite element analysis:

- one lengthened sacroiliac screw fixation in S1 segment (L1);
- one lengthened sacroiliac screw fixation in S2 segment (L2);
- one lengthened sacroiliac screw fixation in S1 and S2 segments respectively (L12);
- one sacroiliac screws fixation in S1 segment (S1);
- one sacroiliac screws fixation in S2 segment (S2);
- one sacroiliac screws fixation in S1 and S2 segments respectively (S12) (Figs. 2–7).

Table 1 Model parameters of pelvic ligaments.

<table>
<thead>
<tr>
<th>Ligament</th>
<th>$K$ (N/mm)</th>
<th>Number of springs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior and capsule</td>
<td>700</td>
<td>27</td>
</tr>
<tr>
<td>Posterior (inner layer)</td>
<td>1400</td>
<td>15</td>
</tr>
<tr>
<td>Intersosseous</td>
<td>2800</td>
<td>8</td>
</tr>
<tr>
<td>Sacrospinous</td>
<td>1400</td>
<td>9</td>
</tr>
<tr>
<td>Saerotuberous</td>
<td>1500</td>
<td>15</td>
</tr>
<tr>
<td>Superior pubic</td>
<td>500</td>
<td>24</td>
</tr>
<tr>
<td>Arcuate pubic</td>
<td>500</td>
<td>24</td>
</tr>
</tbody>
</table>

In order to assemble, tie constraints were applied between the interaction surfaces of sacrum, sacroiliac cartilage and ilium, between the interaction surfaces of pubic rami and interpubic disc, and between the bone-implant

**Conclusion:** In a finite element model of type C pelvic ring disruption, S1 and S2 lengthened sacroiliac screws should be utilized for the fixation as regularly as possible and the most stable fixation is the combination of the lengthened sacroiliac screws of S1 and S2 segments. Even if lengthened sacroiliac screws cannot be systematically used due to specific conditions, one sacroiliac screw fixation in S1 and S2 segments respectively is recommended. No matter which kind of sacroiliac screw is used, if only one screw can be implanted, the fixation in S2 segment is more recommended than that in S1.

**Level of evidence:** Experimental study Level III.

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Table 2  Model parameters of various kinds of material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Element type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>18,000</td>
<td>0.3</td>
<td>Shell element</td>
</tr>
<tr>
<td>Trabecular bone</td>
<td>150</td>
<td>0.2</td>
<td>Tetrahedral element</td>
</tr>
<tr>
<td>Sacroiliac cartilage</td>
<td>1000</td>
<td>0.3</td>
<td>Hexahedral element</td>
</tr>
<tr>
<td>Interpubic disc</td>
<td>5</td>
<td>0.45</td>
<td>Hexahedral element</td>
</tr>
<tr>
<td>Screw</td>
<td>114,000</td>
<td>0.3</td>
<td>Hexahedral element</td>
</tr>
</tbody>
</table>

Figure 1  Pelvic three-dimensional finite element model (the left is frontal view and the right is posterior view).

Figure 2  Sketch map of L1.

Figure 3  Sketch map of L2.

Figure 4  Sketch map of L12.

Figure 5  Sketch map of S1.

interfaces in the screw thread regions. Frictionless sliding contact was applied between the interaction surfaces of the bone-implant interfaces in the screw stem regions. Penalty contact with a friction coefficient of 0.3 was applied between the interaction surfaces of fractures. Boundary condition was simulated with the rotation center of the acetabula being fixed. 600N vertical load was imposed to the superior surface of sacrum.
Results

The results of this study shows:

- the stability of one lengthened sacroiliac screw fixation in S1 or S2 segment is superior to that of one sacroiliac screws fixation in the same sacral segment;
- the stability of one lengthened sacroiliac screw fixation in S1 and S2 segments respectively is superior to that of one sacroiliac screw fixation in S1 and S2 segments respectively;
- the stability of one lengthened sacroiliac screw fixation in S1 and S2 segments respectively is superior to that of one lengthened sacroiliac screw fixation in S1 or S2 segment;
- the stability of one sacroiliac screw fixation in S1 and S2 segments respectively is markedly superior to that of one sacroiliac screw fixation in S1 or S2 segment;
- the vertical and rotational stability of lengthened sacroiliac screw fixation or sacroiliac screw fixation in S2 is superior to that of S1 (Table 3).

Discussion

Sacroiliac screw has been an important progress in the treatment of posterior pelvic ring injury during the past 20 years. However, some clinical reports showed that conventional sacroiliac screw may not universally result in sufficient stable fixation. Keating et al. [6] obtained an anatomic or near-anatomic pelvic reduction with sacroiliac screws in 84% of patients but had a 44% malunion rate finally. Damian et al. [7] found that in the management of vertical sacral fracture with sacroiliac screws, fixation failure and loss of reduction are more likely to happen. So lengthened sacroiliac screw arised.

The so-called "lengthened sacroiliac screw" is a single screw through bilateral sacroiliac joints and sacral body. So far, there is no unified appellation for this kind of screw. Some reports called it "trans-sacral fixation" [1], and other reports called it "significantly longer screw", "specific longer screw" [8] or "transiliac-transsacral screw" [2]. This paper used "lengthened sacroiliac screw" to describe it. Because the lengthened sacroiliac screw obtains fixation by traversing bilateral sacroiliac joints and sacral body, so this technique can solve the problem of bilateral sacroiliac joint fractures and dislocations [2]. In addition, because the screw is significantly longer than conventional sacroiliac screw, so even if it is used for unilateral sacroiliac joint injury or sacral fracture, it also can in theory increase firm degree of fixation. So the lengthened sacroiliac screw is more applicable to repair surgery after first failure of the sacroiliac screw fixation [1] and pelvic posterior ring injury combining osteoporosis. Therefore, the lengthened sacroiliac screw is the improvement of sacroiliac screw, and is also a special kind of sacroiliac screw.

The following content needs to be pointed out. Firstly, although Tile C pelvic ring injury involves an unstable anterior ring which should be fixed, considering the diversity of anterior pelvic ring fixation styles which certainly will affect the stability of posterior pelvic ring, we did not imitate anterior pelvic ring injury and its fixation but just kept the anterior pelvic ring normal state. Although the value related to the stability of posterior pelvic ring is small, it does not affect the stability comparison between several models. Secondly, we reserved multiple important pelvic ligaments to maximize the simulation of the pelvic stability while we did not imitate the muscles and made no attempt to simulate the additional stability of these muscles to exclude any unpredictable forces that might influence the measurements [9]. Thirdly, there are a variety of forms of sacral comminuted fractures and we cannot simulate all the status of the fractures accurately. Therefore, the unilateral sacral fracture was imitated with one sagittal plane through unilateral sacral foramina which can simulate the type of sacral fracture (Denis II) typically. The straight smooth fracture surface was convenient to model standardization and helped to avoid affecting meshing and accuracy of the following calculation. Fourthly, the positions of pelvises were adjusted to the same horizontal as the top surface of pubic symphysis.

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<table>
<thead>
<tr>
<th>Normal pelvis</th>
<th>Downward translation (mm)</th>
<th>Backward angle displacement (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0.183</td>
<td>0.081</td>
</tr>
<tr>
<td>L2</td>
<td>0.164</td>
<td>0.075</td>
</tr>
<tr>
<td>L12</td>
<td>0.147</td>
<td>0.069</td>
</tr>
<tr>
<td>S1</td>
<td>0.188</td>
<td>0.087</td>
</tr>
<tr>
<td>S2</td>
<td>0.170</td>
<td>0.076</td>
</tr>
<tr>
<td>S12</td>
<td>0.148</td>
<td>0.074</td>
</tr>
</tbody>
</table>
and the bottom surface of sacrum, which simulated the state of normal double legs standing. Fifthly, the finite element model building in this study dose not rely on bone mineral density. Consequently, our findings theoretically apply to both young patients and older patients.

This study found that the direction of sacral translation was mainly in the direction of the applied force, which is consistent with the result of a cadaveric pelvic biomechanical research [9]. We found that vertical load on posterior pelvic ring led to downward translation in coronal and sagittal plane and backward rotation in sagittal plane of the middle sacral superior surface and the ventrodorsal and mediolateral displacement of this part was almost zero. Therefore, the comparison of vertical and rotational stability of two kinds of complexes of posterior pelvic rings and sacroiliac screws can reflect the fixation effects of all fixation methods. This study's results suggest that S1 and S2 lengthened sacroiliac screws (L1 and L2) should be utilized for the fixation in unilateral sacral fractures of Tile C pelvic ring injury as far as possible and the most stable fixation is the combination of the lengthened sacroiliac screws of S1 and S2 segments (L12). Even if lengthened sacroiliac screws cannot be used due to limited conditions, one sacroiliac screw fixation in S1 and S2 segments respectively is recommended (S12). In addition, this study shows that the vertical and rotational stability of lengthened sacroiliac screw and sacroiliac screw fixation in S2 is superior to that of S1. Thus, we conclude that the fixation effect of various sacroiliac screws may be partly related to the pelvic anatomy. We suggest that no matter which kind of sacroiliac screw is applied, if only one screw is implanted, the fixation in S2 segment is more recommended than that in S1.

S1 and S2 constitute the anatomic basis for sacroiliac screws’ fixation. Misplacement of sacroiliac screws may reduce the strength of fixation and additionally lead to neurologic or vascular complications [10]. Our radiological anatomy study on posterior pelvic rings of normal adults shows that the horizontal sacroiliac screws’ safe insertion space of S1 is larger than that of S2 [11]. Accordingly, most of sacroiliac screws were placed in S1 segment clinically [10]. Some reports on the clinical application of sacroiliac screws show that compared with S1 segment, the screw misplacement rate in S2 segment is higher [9, 12, 13]. On the contrary, some clinical reports suggest that sacroiliac screw insertion in S2 level with conventional C-arm fluoroscopy is also safe and feasible [14]. Because the fracture lines of vertical sacral fractures (Tile C type) approximately lie in sagittal planes, this kind of posterior pelvic damage suits for horizontal sacroiliac screw placement [15], which is conducive to fracture reduction and fracture ends’ compressing. And the bony structure of S2 segment runs horizontally, which exactly suits for horizontal sacroiliac screw placement. Furthermore, a study [8] shows that the S2 segment provides a larger osseous site for screw insertion than S1 in dysmorphic sacrums and the significantly longer screws are possible in S2 compared with the dysmorphic S1 segment. Another study also indicates that the S2 segment may be a primary fixation opportunity in patients with sacral dysmorphism [16]. Combined with this mechanical study results, sacroiliac screw fixation in S2 is a good choice in the treatment of some unilateral vertical sacral fractures if technical conditions allow.

Some mechanical principles may underlie the basis for the effectiveness of lengthened sacroiliac screws. Firstly, Gorczyca et al. [17] reported that vertical shear was the major force vector across the posterior pelvis ring, and authors [18, 19] reported that the load was distributed along the entire length of the sacroiliac screw. So a longer sacroiliac screw may distribute the load better and resist displacement while decreasing stresses at the tip of the screw [2]. The longest distance in sacroiliac complex is the lengthened sacroiliac screw path. The use of lengthened sacroiliac screw going through the sacral body in a unilateral sacral fracture seems evident according to biomechanical principles. This study found that the stress distribution of lengthened sacroiliac screws was more dispersive and homogeneous than that of conventional sacroiliac screws. This effectively supports the aforementioned biomechanical principle which has not been clarified before. Secondly, conventional sacroiliac screws play a part in fixation by combining two or three cortices lateral to the injury and zero or one cortex medial to the injury, which provide unbalanced fixation and may lead to loss of reduction. On the contrary, lengthened sacroiliac screws combine cortices of sacrum and ilium both lateral and medial to the injury, which may improve fixation effect and minimize loss of reduction by providing continuous balanceable fixation.

However, this study showed that the translation and rotation stability of the sacrum in intact pelvis were clearly superior to that of any posteriorly fixed pelvis. Therefore, we suggest that premature weight-bearing should be avoided lest internal fixation failure and loss of reduction, even though the most stable fixation is applied.

It needs to be emphasized that there are many variation phenomenons in sacrums as mentioned, and not all pelvic posterior rings fit into the placement of lengthened sacroiliac screws [20, 21]. For example, in case of high L5-S1 lordosis, the position of the S1 body is not always aligned with both sacral ala. Thus, the lengthened screw is not always feasible without extraosseous trajectory. Similarly, S2 may not always have the safe space for the lengthened sacroiliac screw placement either. So anyway, it is necessary to read the pelvic CT carefully before the operation. The concrete scheme of sacroiliac screw placement can be determined only after exclusion of all variations interfering with the screw placement.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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