

Comparison of Biomechanical Characteristics and Pelvic Ring Stability Using Different Fixation Methods to Treat Pubic Symphysis Diastasis

A Finite Element Study

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Abstract: The intention of this study was to compare the biomechanical characteristics using 5 internal fixation methods used clinically to stabilize a pubic symphysis diastasis (PSD, Tile type B1).

A 3-dimensional finite element model of PSD was simulated using 5 implants, including single superior plate (Single-Plate), superior and anterior plate (Dual-Plate), single cannulated screw (Single-Screw), crossed dual cannulated screws (Cross-Screw), and parallel dual cannulated screws (Para-Screw). Three loads were distributed in all models, including dual-leg standing, single-leg stance, and rotation. To evaluate the biomechanical properties, the construct stiffness, the stress distribution, and the von Mises stress were recorded and analyzed. To evaluate pelvic ring stability, the micromotion of the pubic symphysis and iliosacral joint was analyzed.

Disruption of pubic symphysis dramatically decreased the pelvic ring stability. Cross-screw and Para-Screw showed higher stiffness than other methods. All implants endured the maximum von Mises stress under single-leg stance. For Plate-Screw system, the maximum stress occurred at a place where it strides over pubic symphysis and adjacent Plate-Screw interface. The single implant and Para-Screw had a tendency to fail. Para-Screw showed the best fixation effect under dual-leg conditions. Cross-screw showed superior antishearing force capacity under single-leg stance. Dual-Plate provided maximum antihorizontal rotation. Para-Screw provided the maximum stabilization for the posterior pelvic ring.

This study showed the biomechanical advantages of dual-implant for PSD only from the finite element view. The Para-Screw provided high construct stiffness under 3 load conditions. The single implant and Para-Screw had a tendency to fail. The better anterior and posterior pelvic stabilization were obtained by the dual-implant fixation than other methods. Therefore, the Cross-Screw and Dual-Plate fixation methods should be preferred in the treatment of pubic symphysis from the finite element view.

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Abbreviations: Cross-Screw = crossed dual cannulated screws, Dual-Plate = superior and anterior plate, Nor = normal condition, Para-Screw = parallel dual cannulated screws, PSD = pubic symphysis diastasis, Single-Plate = single superior plate, Single-Screw = single cannulated screw.

INTRODUCTION

Traumatic pubic symphysis diastasis (PSD) is an uncommon injury caused by high energy.¹ Epidemiologic studies show that PSD accounts for 13% to 16%² of pelvic ring injuries and 4.6%³ of all fractures. The pubic symphysis is an oligodynamic joint, which consists of bilateral pubic bones and fibrocartilaginous disc. It plays a significant role in maintaining the stability of pelvic ring. The structure provides a strong union between 2 innominate bones in order to maintain the stability of anterior pelvic ring. Many ligaments contribute to pelvic stability, such as anterior sacroiliac, posterior sacroiliac, interosseous sacroiliac, sacrospinous, sacrotuberous, superior pubic, and arcuate pubic ligaments. Generally, the PSD exceeds 25 mm, suggesting pelvic ring instability caused by damaged superior pubic, arcuate pubic, anterior sacroiliac, and sacrospinous ligaments.² Under such circumstances, the PSD causes pelvic ring instability and surgery is indicated to restore stability.

There are several fixation methods to treat PSD, such as external fixation, tension band wiring, plate fixation, cannulated screw fixation, and so on.¹ The Plate-Screw system was considered the gold standard for the treatment of PSD.⁴ However, this method leads to complications such as iatrogenic nerves and blood vessels injury, wound disorders, spermatic cord injury, and so forth.^{5,6} In order to avoid these issues, a minimally invasive fixation method was introduced. Mu et al⁵ reported a minimally invasive technique of percutaneous single or dual cannulated screw fixation, which provides enough stability and reduces complications in PSD. Unfortunately, a high rate (19%–90%) of implant failure, loss of reduction, and revision surgery were reported.^{1,7}

The high rate of fixation failure is attributed to the stresses on pubic symphysis. The pubic symphysis is subjected to a variety of forces by body weight, ligament tension, and muscular traction. The superior pubic symphysis endures shearing and compressive, tensile and torsional forces in single-leg stance, dual-leg standing, and rotation, respectively.^{8–10} These forces are absorbed and dissipated by the fibrocartilaginous disc and ligaments with intact pubic symphysis. When pubic symphysis is disrupted, the fixation is intended to provide a stable environment for soft-tissue repair. However, the fixation technique associated with sufficient strength and appropriate biomechanical reduction is unclear.

Therefore, the intention of this study was to compare the postoperative biomechanical characteristics among single plate, dual plate, single cannulated screw, crossed dual cannulated screws (Cross-Screw), and parallel dual cannulated screws (Para-Screw) under dual-leg standing, single-leg stance, and rotation conditions used clinically to stabilize a PSD (Tile type B1) by finite element analysis. Furthermore, the pelvic ring stability was evaluated by analyzing the micromotion of the pubic symphysis and iliosacral joint.

METHODS

This study was done at the Provincial Hospital Affiliated to Shandong University in Jinan, Shandong, China and permission was obtained from the hospital Ethics Committee. Authors had to obtain patient consent before enrolling participants in this study.

Finite Element Models and Implants

A 3-dimensional finite element model was developed from computed tomography scan. The DICOM format files of computed tomography scan were processed by MIMICS 15.0 (Materialise, Belgium). An intact pelvis model with anterior sacroiliac, posterior sacroiliac, interosseous sacroiliac, sacrospinous, sacrotuberous, superior pubic, and arcuate pubic ligaments was created to simulate the normal (Nor) condition (Fig. 1A). To simulate the Tile B1 situation, the PSD model was made by removing superior pubic, arcuate pubic, right anterior sacroiliac, right sacrospinous, and right sacrotuberous ligaments from the Nor model (Fig. 1B).¹¹

Five implants were used in the PSD model, including the single superior plate (Single-Plate), superior and anterior plate (Dual-Plate), single cannulated screw (Single-Screw), Cross-Screw and Para-Screw (Fig. 2). The superior reconstruction plate (Synthes, Oberdorf, Switzerland) was 4-hole and the anterior was 5-hole. The length and diameter of the primary cannulated screws (Synthes, Oberdorf, Switzerland) were 60 and 7.3 mm, respectively. The length and diameter of the additional cannulated screws (Synthes, Oberdorf, Switzerland) were 60, 6.5 mm (Cross-Screw) and 30, 6.5 mm (Para-Screw),

respectively. The construction plates and cannulated screws were inserted into the PSD model using the standard surgical technique.^{5,12} The contact behavior of cortical-screw/bone interfaces was set as a rigid bond and that of plate/bone interfaces as surface-to-surface. The threads and screwheads of cannulated screws were fully fixed into cortical bones. The threads of cortical screws were omitted in order to simplify the models. The intact model without implants had a total of 781,838 elements and 202,616 nodes. The elements for implants were 35,567, 65,388, 20,027, 48,294, and 42,583 for Single-Plate, Dual-Plate, Single-Screw, Cross-Screw, and Para-Screw, respectively. The nodes for implants were 8,604, 15,828, 5,432, 12,394, and 10,784, respectively.

Finite Element Analysis

The finite element analysis was performed by Abaqus 6.13 (3DS, Waltham, MA). Linear elastic isotropic material properties were assigned to all models and implants. All contact elements were defined as deformable elements. The ligaments were simulated as nonlinear spring elements. The properties of bones, ligaments, and implants are shown in Table 1.¹³

The superior segment of S1 of models was fixed. To observe the biomechanical characteristics under specific stresses, 3 types of load condition were used in all models (Fig. 3A), including dual-leg standing, single-leg stance, and rotation. To simulate dual-leg standing, a vertical force of 500 N was distributed to the bilateral acetabulums, respectively. To simulate single-leg stance, a vertical force of 750 N was distributed to the right acetabulum. For rotation, a follower load of 500 N and a torque of 7 Nm were applied to the bilateral acetabulums to simulate right rotation.

The biomechanical characteristics of Single-Plate, Dual-Plate, Single-Screw, Cross-Screw, and Para-Screw models were analyzed and compared with the Nor and PSD models. The construct stiffness was used to compare the construct stability. To evaluate the force condition, the stress distribution and the maximum von Mises stresses were described. The stability of pelvic ring was evaluated under different circumstances by

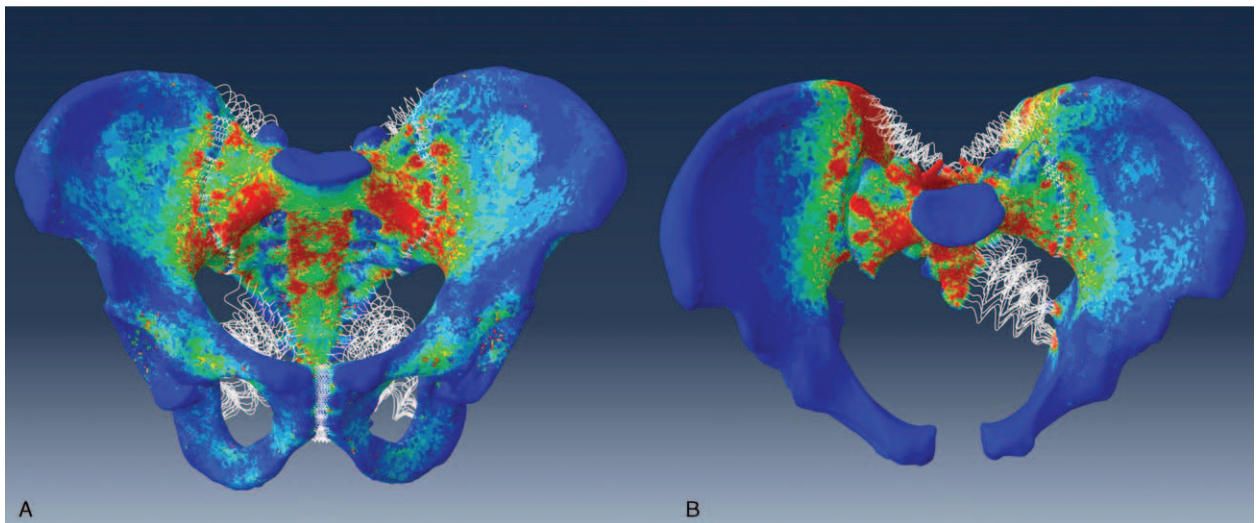


FIGURE 1. The Nor and PSD models. (A) An intact pelvis model with anterior sacroiliac, posterior sacroiliac, interosseous sacroiliac, sacrospinous, sacrotuberous, superior pubic, and arcuate pubic ligaments was created to simulate the normal condition. (B) To simulate the Tile B1 situation, the PSD model was made by removing superior pubic, arcuate pubic, right anterior sacroiliac, right sacrospinous, and right sacrotuberous ligaments from the intact model. Nor = normal bone, PSD = pubic symphysis diastasis.

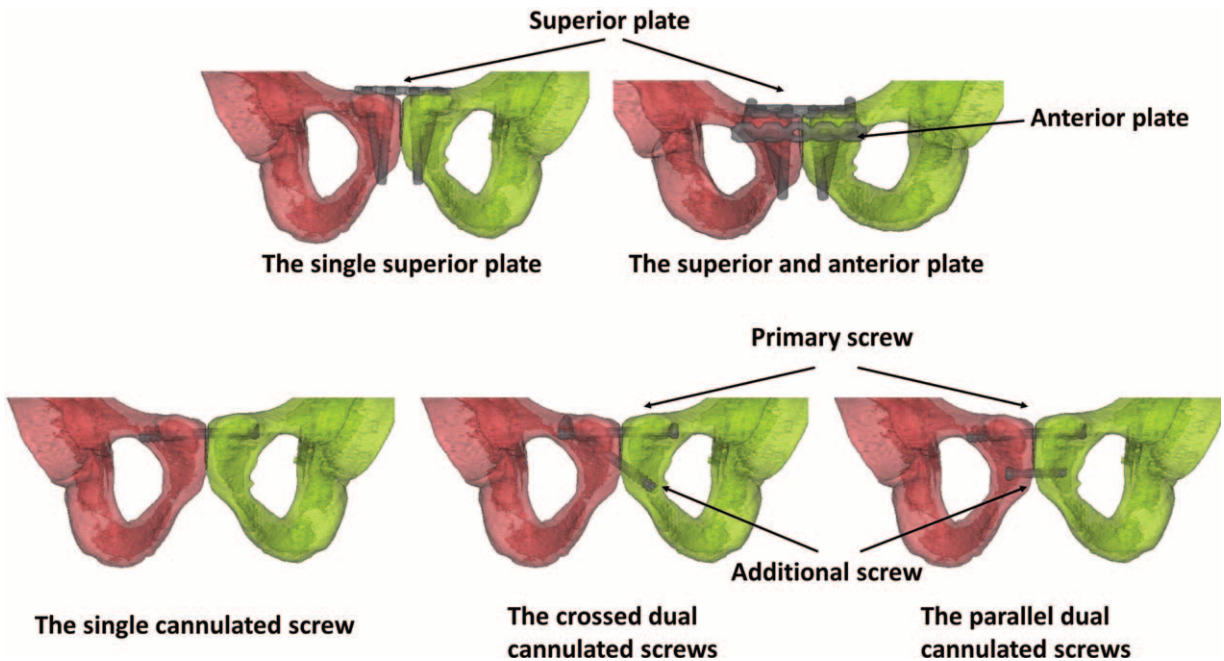


FIGURE 2. The construction plates and cannulated screws were instrumented into the pubic symphysis diastasis (PSD) model using standard surgical techniques, including the single superior plate, superior and anterior plate, single cannulated screw, crossed dual cannulated screws, and parallel dual cannulated screws.

recording the micromotion of anterior and posterior pelvic ring. For anterior pelvic ring, the horizontal displacements under dual-leg standing, the vertical displacements under single-leg stance, and increment of rotational angle under rotation were determined and analyzed (Fig. 3B). For posterior pelvic ring, the micromotion of iliosacral joint in horizontal, coronal, and sagittal planes was determined and analyzed.

RESULTS

Biomechanical Characteristics

The construct stiffness of the Nor, PSD, Single-Plate, Dual-Plate, Single-Screw, Cross-Screw, and Para-Screw models under dual-leg standing, single-leg stance, and rotation condition is displayed in Table 2. When pubic symphysis was

disrupted, the construct stiffness was decreased dramatically under 3 conditions. In general, the construct stiffness was not restored significantly by the 5 internal fixation methods. Dual cannulated screws showed higher stiffness than dual plates, especially in rotational stiffness. The Single-Screw showed almost minimum construct stiffness.

The maximum von Mises stress of implants is described in Figure 4 and Table 3. In general, the implants endured the maximum von Mises stress under single-leg stance. An additional implant was conducive to stress dispersion from a primary implant. Negatively, the additional cannulated screw endured higher stress than the primary cannulated screw in Para-Screw. For Plate-Screw system, the maximum von Mises stress occurred at a place where it strides over pubic symphysis and adjacent Plate-Screw interface. The maximum von Mises

TABLE 1. Material Properties of Finite Element Models

Material	Elastic Modulus, MPa	Poisson Ratio	K, N/m	Number of Springs
Bone				
Cortical bone	18,000	0.3		
Cancellous bone	150	0.2		
Ligaments				
Anterior and capsule sacroiliac ligament			700	27
Posterior sacroiliac ligament			1400	15
Interosseous sacroiliac ligament			2800	8
Sacrospinous ligament			1400	9
Sacrotuberous ligament			1500	15
Superior pubic ligament			500	24
Arcuate pubic ligament			500	24
Implants	114,000	0.3		

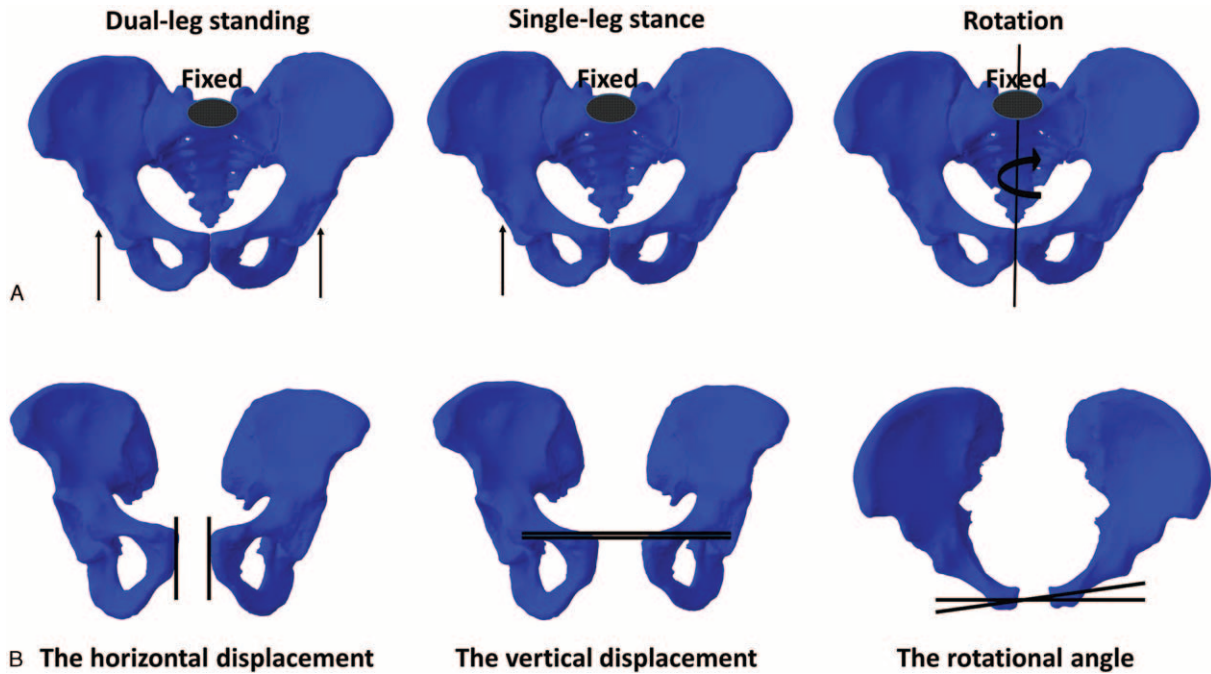


FIGURE 3. Three types of load were applied in all models and micromotion of the pubic symphysis were recorded. (A) The superior segment of S1 of models was fixed. To simulate dual-leg standing, a vertical force of 500 N was distributed to the bilateral acetabulums, respectively. To simulate single-leg stance, a vertical force of 750 N was distributed to the right acetabulum. For rotation, a follower load of 500 N and a torque of 7 Nm were applied to the bilateral acetabulums to simulate right rotation. (B) The incremental micromotion of the pubic symphysis was recorded to evaluate the stability of anterior pelvic ring. The increment of horizontal displacements under dual-leg standing, the incremental vertical displacements under single-leg stance, and increment of rotational angle under rotation were described.

stress with the cannulated screw system occurred at the thread-cortical bone interface. Stress concentration appeared on Plate-Screw system, whereas stress equidistribution was observed in the caudomedial part of cannulated screws.

Pelvic Ring Stability

The incremental micromotion of anterior pelvic ring is shown in Table 4. For dual-leg standing, the increment of horizontal displacement was 0.010 mm and -25.982 mm under intact and PSD conditions. Para-Screw showed the best fixation effect (0.124 mm). For single-leg stance, the incremental vertical displacement was increased dramatically in PSD model (6.228 mm) than in Nor model (0.528 mm). In this situation, Cross-Screw showed superior antishearing force capacity

(0.043 mm). For rotation, the incremental rotation was increased significantly in PSD model (-8.499°) than in Nor model (1.328°). Dual-Plate offered maximum antihorizontal rotation (0.089°).

The incremental micromotion of posterior pelvic ring is shown in Table 5. In general, the PSD model showed extreme instability, especially in horizontal plane. The 2 cannulated screws provided the optimal posterior pelvic ring stabilization. The Para-Screw provided the most stability in horizontal, coronal, and sagittal planes under 3 load conditions. Compared with dual cannulated screws, the Dual-Plate also provided the satisfied posterior stabilization. However, the single implant did not achieve posterior pelvic ring stabilization, especially with single cannulated screw.

TABLE 2. The Construct Stiffness of Models

Load Condition	Innominatum	Nor	PSD	Single-Plate	Dual-Plate	Single-Screw	Cross-Screw	Para-Screw
Dual-leg standing, N/mm	Right	415.973	14.594	51.146	56.249	37.908	62.135	67.577
	Left	483.092	159.949	161.812	151.699	192.976	147.016	153.563
Single-leg stance, N/mm	Right	328.515	14.380	46.216	50.400	35.740	55.584	58.289
	Left	465.839	762.195	131.142	124.709	156.283	120.676	122.709
Horizontal rotation, Nm/Rad	Right	-9.323	-0.256	-1.975	-2.262	-1.407	-3.482	-3.506
	Left	10.234	2.776	18.329	26.475	17.826	21.383	25.673

Cross-Screw = crossed dual cannulated screws, Dual-Plate = superior and anterior plate, Nor = normal condition, Para-Screw = parallel dual cannulated screws, PSD = pubic symphysis diastasis, Single-Plate = single superior plate, Single-Screw = single cannulated screw.

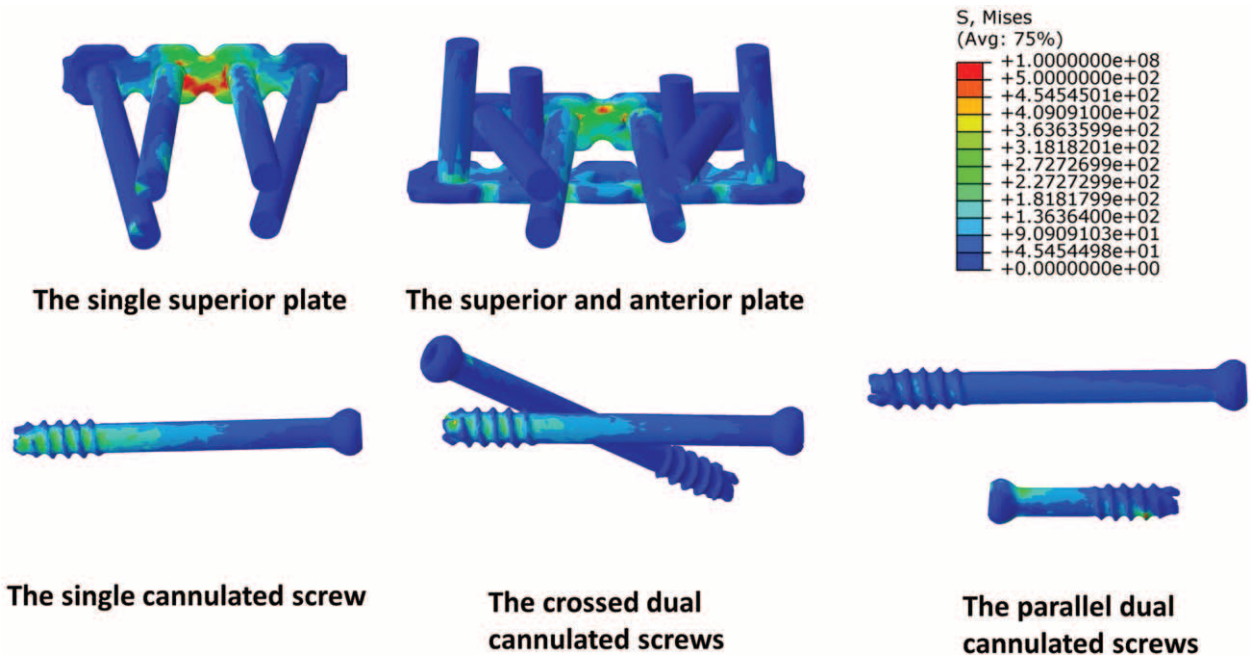


FIGURE 4. The von Mises stress distribution on 5 implants in dual-leg standing. For Plate-Screw system, the maximum von Mises stress occurred at a place where it strides over pubic symphysis and adjacent Plate-Screw joints. The maximum von Mises stress with the cannulated screw system occurred at the thread-cortical bone interface. Stress concentration appeared on Plate-Screw system, whereas stress equidistribution was observed in the caudomedial part of cannulated screws.

DISCUSSION

The pubic symphysis is an amphiarthrodial joint, which consists of bilateral pubic bones and intercalated disc. The pubic symphysis maintains anterior pelvic ring stability and protects organs from trauma. The tensile, shearing, and compressive forces caused by trauma are absorbed and dissipated by the fibrocartilaginous disc and ligaments in intact pubic symphysis. It is generally accepted that the pubic symphysis resists tensile stresses in dual-leg standing, compressive and shearing pressures in single-leg stance, and torsional forces in horizontal rotation. The inferior pubic symphysis endures tractional force.⁹ Pubic symphysis disruption leads to instability. The diastasis exceeding 25 mm due to broken soft tissues is considered an indication for surgery.²

In the current study, we simulated a Tile type B1 model with a disruption of 25.992 mm. In this condition, the stabilization of posterior pelvic ring was affected by the unstable anterior pelvic ring and broken ligaments. Therefore, to

evaluate pelvic ring stability, the micromotion of the pubic symphysis and iliosacral joint was recorded and analyzed in this study.

Open reduction and internal fixation with symphysis plates is thought to be the gold standard.⁴ The Pfannenstiel approach is the most common incision.² However, this method may lead to complications due to extensive exposure, such as iatrogenic nerves and blood vessel injury, wound disorders, and spermatic cord injury.⁵ Further, it is associated with a high rate of implant failure, loss of reduction, and revisional surgery. The implant failure in pubic symphysis was 19% to 90% in previous reports.⁷ The high rate of fixation failure can be attributed to the stresses of pubic symphysis. Pubic symphysis disruption represents a discontinuous bridge, not a fracture. A better understanding of the biomechanical effect by the fixation methods should improve treatment outcome.

Our results show that, when pubic symphysis was disrupted, the construct stiffness of bilateral innominate bones was

TABLE 3. The Maximum von Mises Stress of Implants (MPa)

Load Condition	Implant	Single-Plate	Dual-Plate	Single-Screw	Cross-Screw	Para-Screw
Dual-leg standing	Primary/superior	1645.656	1031.047	1921.717	1268.784	712.291
	Additional/anterior	—	550.762	—	806.743	1337.629
Single-leg stance	Primary/superior	2368.301	1466.172	3397.952	1835.905	1071.481
	Additional/anterior	—	915.016	—	1241.158	2183.438
Horizontal rotation	Primary/superior	1611.929	958.09	1304.797	1661.829	912.259
	Additional/anterior	—	586.085	—	615.604	1359.05

Cross-Screw = crossed dual cannulated screws, Dual-Plate = superior and anterior plate, Para-Screw = parallel dual cannulated screws, Single-Plate = single superior plate, Single-Screw = single cannulated screw.

TABLE 4. The Incremental Micromotion of the Anterior Pelvic Ring

Load Condition	Nor	PSD	Single-Plate	Dual-Plate	Single-Screw	Cross-Screw	Para-Screw
Dual-leg standing, mm	0.010	-25.982	-1.211	-0.495	-0.438	-0.220	0.124
Single-leg stance, mm	0.528	6.228	1.312	0.946	5.622	0.043	1.206
Horizontal rotation, °	1.328	-8.499	-0.312	0.089	-0.185	-0.535	0.626

Cross-Screw = crossed dual cannulated screws, Dual-Plate = superior and anterior plate, Nor = normal condition, Para-Screw = parallel dual cannulated screws, PSD = pubic symphysis diastasis, Single-Plate = single superior plate, Single-Screw = single cannulated screw.

decreased dramatically under 3 conditions. In general, the construct stiffness was not restored by 5 internal fixation methods, this may be attributed to the unstable posterior pelvic ring. In internal fixation, the dual-implant can provide more construct stiffness than the single-implant. Dual cannulated screws showed higher stiffness than dual plates, especially in rotational stiffness. The Single-Screw failed to enhance the stability, which only provided 9.113%, 10.879%, and 15.091% construct stiffness of intact condition under 3 load conditions. These results may be attributed to the inadequacy of single screw to provide a planar fixation observed with plate and dual screws.

The implants endured the maximum von Mises stress under single-leg stance. This phenomenon was attributed to the huge vertical shearing forces. In general, the risk of implant failure depends mainly on excessive stress load. The implant failure in Plate-Screw system involves breakage and screw losing. Stress concentration phenomenon and the maximum von Mises stress occurred at a place where the pubic symphysis strides over and the adjacent Plate-Screw interface in the plate system. In the cannulated screw system, stress concentration was observed on the joints of cortical bone and cannulated screw threads. The caudomedial part of cannulated screw showed stress equidistribution. This result can be explained by the fact that the primary type of failure is a pull-out for

cannulated screws. Surprisingly, the additional cannulated screw endured higher stress than the primary cannulated screw in Para-Screw, due to the short length of inefficient stress dispersion. Even though the stresses were dispersed by 2 implants, the place of stress concentration and the maximum stress had a high rate of implant failure, especially for Para-Screw and Single-Plate. In the present study, we inserted a Para-Screw to enhance the stabilization of the lower pubic symphysis. Unfortunately, this method had a tendency to fail due to the huge stresses. Perhaps, the Cross-Screw is a better choice to maintain balance in lower symphysis stability and implant failure. These results were confirmed by previous reports showing 19% to 90% rate of implant failure.⁷

For dual-leg standing, the increment of horizontal displacement was 0.010 mm and -25.982 mm under intact and PSD conditions. The distance of pubic symphysis was 25.992 mm, which is an indication for surgery. The Para-Screw showed the best fixation effect (0.124 mm) under dual-leg standing with a double pulling force. The incremental vertical displacement of Single-Screw under single-leg stance was 5.622 mm, which meant that a single cannulated screw was not a good option to resist vertical shearing forces. On the contrary, Cross-Screw performed better (0.043 mm) due to an oblique pulling force. For rotation, the Dual-Plate offered maximum antihorizontal

TABLE 5. The Incremental Rotational Angle of the Posterior Pelvic Ring (mm)

Load Condition	Plane	Iliosacral Joint	Nor	PSD	Single-Plate	Dual-Plate	Single-Screw	Cross-Screw	Para-Screw
Dual-leg standing	Horizontal	Right	0.418	29.198	5.575	4.676	5.300	4.266	3.553
		Left	-0.547	-2.426	-0.256	-0.181	-0.236	-0.148	-0.224
	Coronal	Right	0.155	13.064	2.192	1.836	2.224	1.650	1.382
		Left	-0.274	-1.159	-0.192	-0.158	-0.169	-0.146	-0.179
	Sagittal	Right	0.355	1.921	0.716	0.717	2.321	0.374	0.558
Single-leg stance	Horizontal	Right	2.298	39.555	12.142	10.840	11.102	10.297	9.320
		Left	1.299	0.784	3.811	3.936	3.857	3.951	3.865
	Coronal	Right	0.884	19.665	4.743	4.230	4.841	3.903	3.593
		Left	0.575	0.343	1.733	1.792	1.754	1.800	1.759
	Sagittal	Right	0.326	2.853	0.325	0.354	2.795	-0.241	0.146
Horizontal rotation	Horizontal	Right	0.746	33.720	6.339	5.355	5.840	5.140	4.327
		Left	-0.234	-1.896	0.336	0.431	0.395	0.457	0.389
	Coronal	Right	0.283	13.838	2.462	2.081	2.376	1.953	1.660
		Left	-0.133	-0.922	0.093	0.136	0.128	0.145	0.115
	Sagittal	Right	0.329	-0.420	0.401	0.445	1.511	-0.076	0.162
Left	0.323	0.490	0.851	0.875	0.743	0.917	0.884		

Cross-Screw = crossed dual cannulated screws, Dual-Plate = superior and anterior plate, Nor = normal condition, Para-Screw = parallel dual cannulated screws, PSD = pubic symphysis diastasis, Single-Plate = single superior plate, Single-Screw = single cannulated screw.

rotation due to multiplanar fixation. However, further clinical and biomechanical studies are needed to determine the fixation method in treatment of PSD.

Without intact ligaments, the stabilization of posterior pelvic ring was affected by the fixation methods of anterior pelvic ring. For posterior pelvic ring, the results of this study showed that Single-Plate and Single-Screw displayed the maximum range of motion in horizontal and coronal planes under dual-leg standing. The Single-Screw provided the maximum motion in all the 3 planes. A single implant, especially for cannulated screw, did not provide enough stability for posterior pelvic ring. Similar results were obtained with the single-leg stance and rotation conditions. With the dual-plane or multi-plane fixation, the dual implants provided sufficient antirotational stabilization. Due to the oblique pulling force and crossed screws placement, the Cross-Screw provided antirotation and antishearing forces. However, the intact pelvis is a very complex construct which cannot be simulated perfectly by finite element method. In the present study, we mainly concerned the fixation methods rather than other influencing factors (age, sex, body mass index, and so on). So, the conclusion from the present study should not be a guide for clinical practice easily. Large clinical studies must be investigated before this conclusion can be recommended.

There were other limitations in this study. The finite element models were based on skeleton-ligament system and the muscle forces were neglected, similarly to other finite element studies.^{14–18} A single pelvic model was used for analysis, just the same as other works,^{14–18} which may avoid the high variation rate of bone and ligament characteristics. There were some limitations to simulating a single-leg stance using a simple method. However, this simple single-leg stance model may provide clinical data of implant failure and pelvic ring stability. To avoid the influence by suboptimal position of implants, the hardwares were inserted into the models using the standard surgical technique. This finite element study has only measured the early postoperative stability, but the long-term biomechanical stabilization has not been evaluated. Considering these limitations, the conclusions should be studied using clinical retrospective analysis and biomechanical testing to determine the feasibility.

In conclusion, this study showed the biomechanical advantages of dual-implant for PSD from the finite element view. The Para-Screw provided high construct stiffness under 3 load conditions. The single implant and Para-Screw had a tendency to fail. The better anterior and posterior pelvic stabilization were obtained by the dual-implant fixation than other methods. Therefore, the Cross-Screw and Dual-Plate fixation methods should be preferred in the treatment of pubic symphysis only from the finite element view.

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