A Finite Element Analysis of Sacroiliac Joint Displacements and Ligament Strains in Response to Three Manipulations

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Abstract

Background Clinical studies have found that manipulations have a good clinical effect on sacroiliac joint (SIJ) pain without specific causes. However, the specific mechanisms of manipulations are still unclear. The purpose of this study was to investigate the effects of three common manipulations on the pressures and displacements of SIJ, and the strains of the surrounding ligaments.

Methods A three-dimensional finite element model of the pelvis-femur was developed. The manipulation of hip and knee flexion (MHKF), the manipulation of oblique pulling (MOP), and the manipulation of lower limb hyperextension (MLLH) were simulated. The pressures and displacements of SIJs, and the strains of the surrounding ligaments were analyzed under the three manipulations.

Results The MOP produced the greatest pressure on the left SIJ, at 6.6 MPa, while the MHKF could produce the lowest pressure on the right SIJ, at 1.5 MPa. The displacements of SIJs were all less than 1mm in the three manipulations. The three manipulations could cause different degrees of the strains of ligaments around the SIJs, and the MOP could produce the largest strain of ligaments.

Conclusion The three manipulations all produced small displacements of SIJs, while they caused different degrees of ligament strains, which might be the reason for relieving the SIJ pain. The MOP may be a more effective manual therapy.

Background

The sacroiliac joint (SIJ) is the largest axial joint in the human body, connecting the spine and the lower limbs, and plays the role of transmitting the weight of the upper body to the pelvis and lower limbs [1–3]. The SIJ is composed of an anterior synovial part and a tightly connected ligament part at the rear [4, 5]. The sacrum is wedge-shaped, with the tip from top to bottom and closely inserted into the convex surface of the ilium with a concave surface [6, 7]. In addition, there are some strong intrinsic and extrinsic ligaments [8, 9]. Due to the special anatomical structures, the SIJ stays very stable [10–12]. However, some bone or soft tissue lesions can cause joint instability, which subsequently induces SIJ pain. Recent studies have found that SIJ diseases can also cause low back pain, which accounts for about 14.5% -22.5% [13].

The causes of SIJ pain include pathological bone destruction, traumatic fracture and dislocation, and pain without specific causes [5]. Commonly, abnormal gait, heavy physical exertion, leg length discrepancy, inflammation, scoliosis, lumbar fusion surgery with fixation of the sacrum may be the factors that cause SIJ pain without specific causes [14]. The mechanism may include the following processes. Pathogenic factors acting on the auricular surface of the sacrum and ilium may cause the injury of ligaments or muscles around SIJs, which will result in slight movement of SIJs, making the joints difficult to reset. Finally, the mechanical environment of the joints appears imbalanced and the soft tissues are damaged. This condition is clinically referred to SIJ subluxation [4]. Pathological bone destruction and traumatic fracture and dislocation need surgeries [15–18], while SIJ pain without specific causes is usually treated with manipulations [19, 20].

There are several common manipulations, including the manipulation of hip and knee flexion (MHKF), the manipulation of oblique pulling (MOP), and the manipulation of lower limb hyperextension (MLLH). A large number of studies have reported that manipulations have a good effect on the treatment of SIJ subluxation [19–21]. Different types of SIJ subluxation require different manipulations [22, 23]. Some authors considered that the manipulations reduced the pain by pulling the subluxated SIJ back [23–25]. Others believed that the SIJ was very stable, and the pain relief was the result of relieving the spasm of the ligaments and muscles around the SIJ [26, 27]. However, the mechanisms of manipulations of the SIJ subluxation are not clear at present. Is it possible to pull the subluxated SIJ back with manipulations? Can manipulations cause ligament strain around the joints? None of these issues have been studied. In this study, the pelvic-femur finite element model is used to investigate the specific mechanisms of the three manipulations on the SIJ and its surrounding ligaments.

Methods

Model construction

A 3D finite element model of the SIJ was developed. 3D models of the sacrum, the ilia and femurs were reconstructed from computed tomography (CT) images of a healthy male volunteer (34 years old, 170 cm of height, and 65 kg of weight) using the Mimics 20.0 (Materialise Company, Leuven, Belgium), where the cortical and cancellous regions of the bones were distinguished. 0.5 mm thick axial slices spanning the entire pelvis were selected for model construction. All surface models were meshed using Geomagic 2013 (Raindrop Company, Marble Hill, USA). The cartilages in the SIJ were reconstructed with a uniform thickness, where the regions of the articular surfaces were based on CT images, and the thicknesses of the cartilages were acquired from the literature. The thickness of the sacral and iliac cartilages had 2 mm and 1 mm of thicknesses, respectively. The bone end-plate thicknesses of the sacral and iliac parts of the cartilage were assumed to be 0.23 mm and 0.36 mm, respectively. The gap between two cartilages was set to be 0.3 mm [12]. The material properties chosen from previous studies [12, 28] were summarized in Table 1.

Table 1
Material properties of the sacrum, ilium, femur, pubic symphysis and endplate.

		Young's modulus (MPa)	Poisson's ratio
Sacrum	Cortical	12000	0.3
	Cancellous	100	0.2
Ilium	Cortical	12000	0.3
	Cancellous	100	0.2
Femur	Cortical	15000	0.3
	Cancellous	100	0.2
Pubic symphysis		5	0.45
Articular cartilage		100	0.3
Endplate		1000	0.4

The anterior sacroiliac ligament (ASL), long posterior sacroiliac ligament (LPSL), short posterior sacroiliac ligament (SPSL), interosseous sacroiliac ligament (ISL), sacrospinous ligament (SS), and sacrotuberous ligament (ST) complexes were modeled as 3D tension-only truss elements. The attachment regions were chosen according to the literature [12]. Two fresh cadaver dissections were used to observe the ligaments' positions and orientations. The ASL was made up of numerous thin bands, which spanned the ventral surface of the SIJ, connecting the lateral aspect of the sacrum to the margin of the auricular surface of the ilium. The LPSL extended from the posterior superior iliac spine to the third and fourth transverse tubercle of the back of the sacrum. The SPSL lay deep to the LPSL and consisted of large fibers attaching the lateral aspect of the dorsal sacral surface to the tuberosity of the ilium. The ISL lay in the intra-articular space and was composed of a series of short strong fibers connecting the tuberosities of the sacrum and ilium. The SS was a thin triangular ligament, and connected the ischial spine to the lateral border of the sacrum. The ST was behind the sacrospinous ligament, which attached the ischial tuberosity to the lateral border of the sacrum. The material properties of each ligament were obtained from the literature [28]. In total, the model contained 340.441 elements and 122,549 nodes.

Model Validation

To validate the developed models, two tests were performed. For the pelvic model, compared with a previous study [29], the distribution of principal strain on the cortical bone of the pelvic was estimated, under the same loading and boundary conditions for the single-legged stance.

For the sacrum model, the relationship between load and displacement was compared to that in previous studies [12, 30, 31]. To simulate the cadaveric experiment, the bilateral ilia were fixed. Under five translational forces (anterior, posterior, superior, inferior, and mediolateral) of 294 N and three moments (flexion, extension, and axial rotation) of 42 N m, the displacements of a node lying in the mid-sagittal plane between the inferior S1 and superior S2 vertebral endplates were calculated.

Three common manipulations were selected based on their popularity and validity. The point and orientation of applied forces were decided by previous studies [32, 33]. In addition, the magnitudes of the forces were determined by collecting the manipulative power of five therapists' through a biomechanical testing machine. The detailed loading and boundary conditions as well as the x-, y-, and z-axis are described in Fig. 1. The contact pressures and the displacements of SIJ, and the ligament strains for the three manipulations were then investigated using Abaqus 2018 (Dassault Systemes S.A Company, Massachusetts USA).

The manipulation of hip and knee flexion

The patient lay supine while the therapist flexed the patient's hip and knee as much as possible, with pronation. Then, the therapist pushed down the knee. Thus, the left hip joint was assumed to be fully constrained. The most posterior regions of the scrum and posterior superior iliac spine were fixed. The left hip was flexed to 155° and was intorted to 35°. Then, a compressive (downward) force of 600N along the ventral-dorsal direction was simultaneously applied at the end of left femur.

The manipulation of oblique pulling

The patient was in the side-lying position and the therapist stood on patient's ventral side. The therapist placed one hand on the dorsal of sacrum so as to fix the patient's position, with the other hand on the anterior superior spine, pushing the ilium toward the back. Thus, the most region of sacrum and the right iliac crest were fixed. Then, a push force of 600N along the ventral-dorsal direction which was parallel to left SIJ surface was applied on the left anterior superior spine.

The manipulation of lower limb hyperextension

The patient lay in a prone position and the leg being treated was hyperextended at the hip so that the anterior superior spine could just lift off the bed. Then, the therapist applied a downward force to the iliac crest being treated. Thus, the right lateral region of ilium and the right pubic tubercle were fixed. Then, a push force of 600N along the dorsal-ventral direction which was parallel to left SIJ surface was applied on the left iliac crest. The point of applied force was the midpoint between the highest point of the iliac crest and the posterior superior spine.

Results

The distribution of principal pressure was mainly located in the upper and posterior area of the acetabulum, extending to the iliac crest, the incisura ischiadica major, and the rear acetabulum. The distribution and maximum value of pressure were consistent with those reported in a previous study [29]. Figure 2 showed that the displacements under eight loading conditions were in agreement with those in not only an experimental study but also some computational studies [12, 30, 31].

The distribution of contact pressures on the SIJ surface of sacrum are shown in Fig. 3. More pressure was observed on the left SIJ for the three manipulations. Among them, the MOP could produce the highest pressure on the left SIJ, at 6.6 MPa, while the MHKF could produce the lowest pressure on the right SIJ, at 1.5 MPa.

In MHKF, the displacements of the left SIJ were 0.120, 0.033, and 0.043 mm in the superior-inferior (SI), anterior-posterior (AP), and medial-lateral (MI) directions, respectively. In MOP, the displacements were 0.048, 0.962, and 0.117 mm in the SI, AP, and MI directions. In MLLH, the displacements were 0.013, 0.114, and 0.060 mm in the SI, AP, and MI directions. The MOP could produce the largest displacement in the AP and MI directions, while the MHKF could cause the largest displacement in the SI direction. The displacements of the left SIJ are shown in Fig. 4.

The strains of six ligaments for three manipulations are shown in Fig. 5. For most of ligaments, the strain of the left ligament was greater than that of the right ligament under the three manipulations. In MHKF, the left SS, ASL and ST had the highest strain values, which were 1.6%, 1.1% and 0.7%. The MLLH could produce the lowest strains of ligaments, while the MOP could cause the highest strains of ligaments. The left ISL and LPSL had the highest strain values in MLLH, which were 0.8% and 0.3%, respectively. In MOP, the left SS, ASL, ST had the highest strain values, which were 3.1%, 1.6%, 1.1%, respectively.

Discussion

SIJ pain is a common disease that affects 90% of adults throughout their lives [2]. Manipulations have a good effect on SIJ pain without specific causes. However, the effects of manipulations on the SIJ and the ligaments have not been clear yet. In this study, the three-dimensional finite element model was used to quantitatively analyze the effects of three manipulations on the displacements of SIJ and the strains of surrounding ligaments, which provided a theoretical basis for the indications of manipulations.

The anterior part of the SIJ is the synovium, which can move slightly, and the posterior part is the interosseous ligament, which mainly plays a role in maintaining the stability of the joint. Walker et al. [34] found that the SIJ had a range of motion of less than 3 mm and a rotation of no more than 2° in a standing or sitting position. Some researchers found that the slip of the SIJ did not even exceed 1 mm [35]. In this study, it was found that the MOP could produce the maximum displacement of the SIJ with the value of 0.962 mm among the three manipulations, while the MLLH could cause the minimum displacement of the SIJ and the value was 0.114 mm. The displacements of SIJ under the three manipulations were all less than 1 mm, which was consistent with the previous studies [34, 35].

In MLLH, neither of the sacrum and iliac bone was fixed directly. As a result, they moved simultaneously during the process. Therefore, the relative displacement of the joint surface was small. The displacement produced by MHKF was also small, the reason might be related to the point of force at the distal femur. The displacement produced by MOP was the largest, considering that the point of force was on the pelvis, and the direction of force was medial-lateral. The MOP could produce the largest displacement in the AP and MI directions, and the MHKF could produce the largest displacement in the SI direction. The biomechanical properties of manipulations can provide a theoretical basis to choose manual therapy.

Ligaments play an important role in maintaining the stability of the pelvis. Sichting et al. [36] found that ligaments were the mechanical stabilization device of the pelvis. Bohme et al. [37] observed that the ASL and ST had the greatest load with 80% and 17% of the total load under the anteroposterior compression pelvic injuries and that the SS played an important role in the vertical stability of the pelvis. Eichenseer et al. [31] considered that ligaments around the SIJ could limit the movement of the SIJ and reduce the stress of the SIJ. In this study, it was found that the three manipulations could cause different degrees of strain on the ligaments around the SIJ. In MOP, the patient's sacrum was fixed relatively and the point of force was on the anterior superior iliac spine and the direction of the force was a MI direction. Therefore, the MOP could cause the largest strain of the ligaments among the three manipulations. The ligament strains produced by MLLH and MHKF were smaller. It might be related to the point and direction of manipulative force as well as the style of pelvic fixation. These results indicated the SS, ASL and ISL had the greatest strains under the three manipulations, which was consistent with the previous studies [12, 31].

In MLLH, the displacement was the smallest, and the ligament strains were also the smallest. In MOP, the displacements and the ligament strains were both the largest. It can be seen that the displacements of SIJ and the ligament strains remain consistent under the three manipulations. These results also prove the reliability and effectiveness of the model.

Szadek et al. [38] found that there were substance P and calcitonin gene-related peptide positive nerve fibers on the SIJ cartilage and surrounding ligaments, indicating that the pain source of SIJ might come from cartilage and ligament tissues. So, is it possible to reduce the pain by pulling the subluxated SIJ back, or by alleviating the spasm of the surrounding ligaments? Chen et.al [39] believed that manipulations were unlikely to pull the SIJ back. The clicking sound and the sense of movement during the manipulative process were likely to be due to the movement of attachment of the SIJ or L5/S1 facet joints. Tullberg et al. [26] argued that manipulations could not change the position of the SIJ, and the cause of pain relief was related to the soft tissues around the joints. Ivanov et al. [40] also considered that the ligaments around the SIJ contained a lot of nerve tissues, and even if a small strain occurred, it would cause pain. Base on the results of this study, the displacements of the SIJ were all less than 1 mm under the three manipulations. In fact, there are lots of muscles and other soft tissues around the SIJ in human bodies. Hence, it can be estimated that the displacement will be smaller in patients. Therefore, it is considered that manipulations are difficult to pull the SIJ back. However, the manipulations could cause different degrees of strains on the surrounding ligaments. Although the ligament strains were small, it could still relieve the spasm of the surrounding ligaments and reduce pain.

There are some limitations in this study. First, our finite element model is based on the geometry and material properties of individual pelvic bones and ligaments in a single male case. However, it is well known that anatomical structures of the pelvis are very different, which must be considered when drawing conclusions in clinical. Second, although muscles and other soft tissues are most likely to participate in maintaining pelvic stability, the effects of them on the pelvis are not considered in this model. Third, the ligaments' characteristics are regarded to be linear. Fourth, there is no unified standard for manipulations currently. So, the specific processes of manipulations are simulated and simplified based on plenty of physicians' experience.

Conclusions

In conclusion, this study was the first to analyze the effects of the three manipulations on the pressures and displacements of the SIJ, and the strains of the surrounding ligaments. The results showed that the displacements of the SIJ produced by the three manipulations were small, while the three manipulations could produce different degrees of ligament strains, which might be the reason for relieving the SIJ pain. The MOP may be a more effective manipulation among the three manipulations.

Abbreviations

SIJ: Sacroiliac joint; MHKF: The manipulation of hip and knee flexion; MOP: The manipulation of oblique pulling; MLLH: The manipulation of lower limb hyperextension; ASL: Anterior sacroiliac ligament; ISL: Interosseous sacroiliac ligament; SS: Sacrospinous ligament; ST: Sacrotuberous ligament; LPSL: long posterior sacroiliac ligament; SPSL: Short posterior sacroiliac ligament; AP: Anterior-posterior direction; SI: Superior-inferior direction; MI: Medial-lateral direction.

Declarations

Ethics approval and consent to participate

The study was approved by Ethics Committee of the First Affiliated Hospital of University of South China. Written informed consent was available, and participant involved gave his consent for the use of individual data and experimental data.

Consent for publication

Not applicable.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

ZX and SQZ carried out the finite element analysis and drafted the manuscript. YKL, LQL and KW participated in the study design and discussion of the clinical results. ZYF and DL constructed the finite element models, performed the biomechanical analysis. All of the authors read and approved the final manuscript.

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Figures

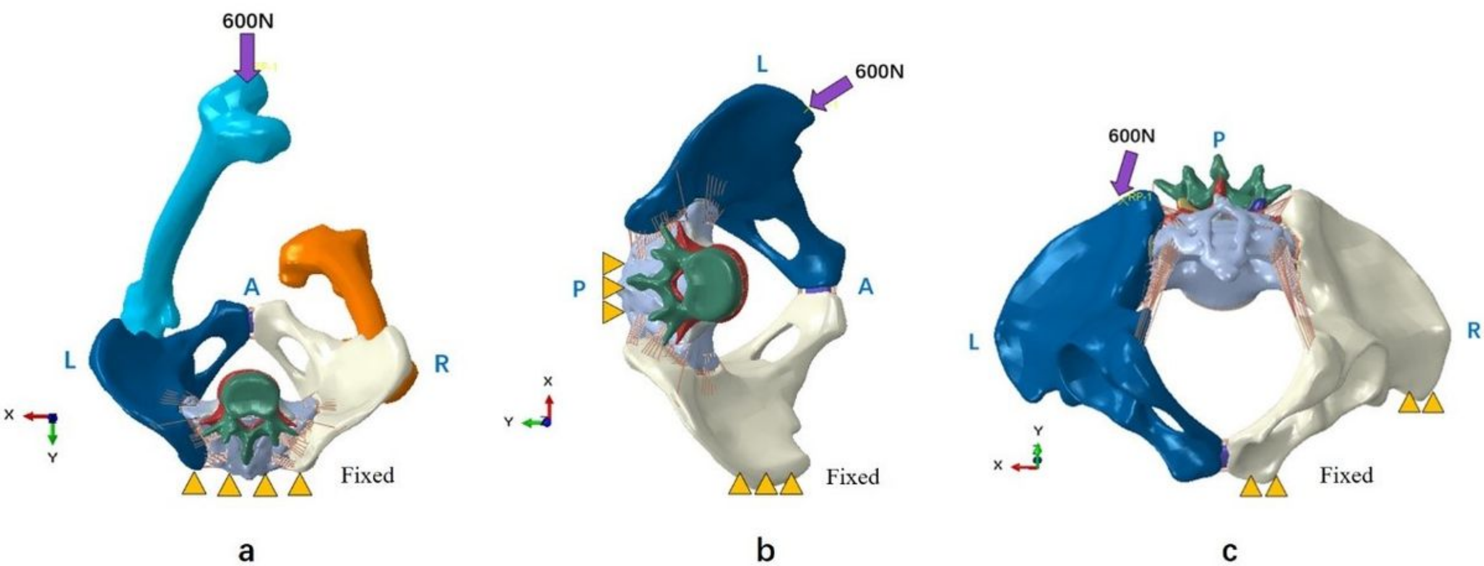

Figure 1

Loading and boundary conditions for the three manipulations. a The manipulation of hip and knee flexion; b The manipulation of oblique pulling; c The manipulation of lower limb hyperextension

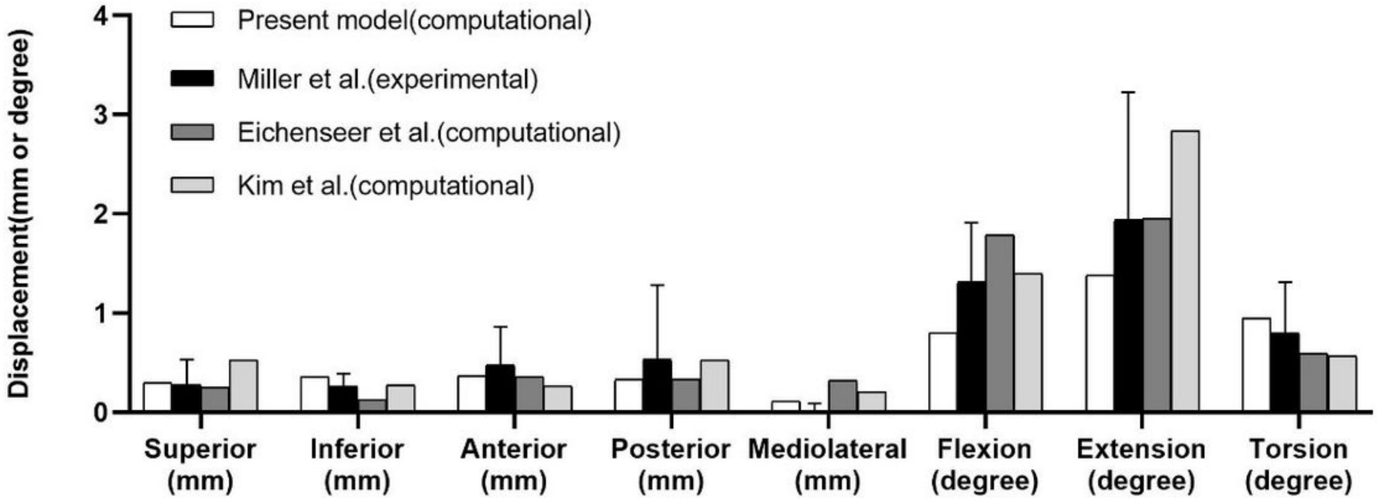

Figure 2

Comparison of sacral displacements under eight loadings comparable to those in previous experimental and computational studies.

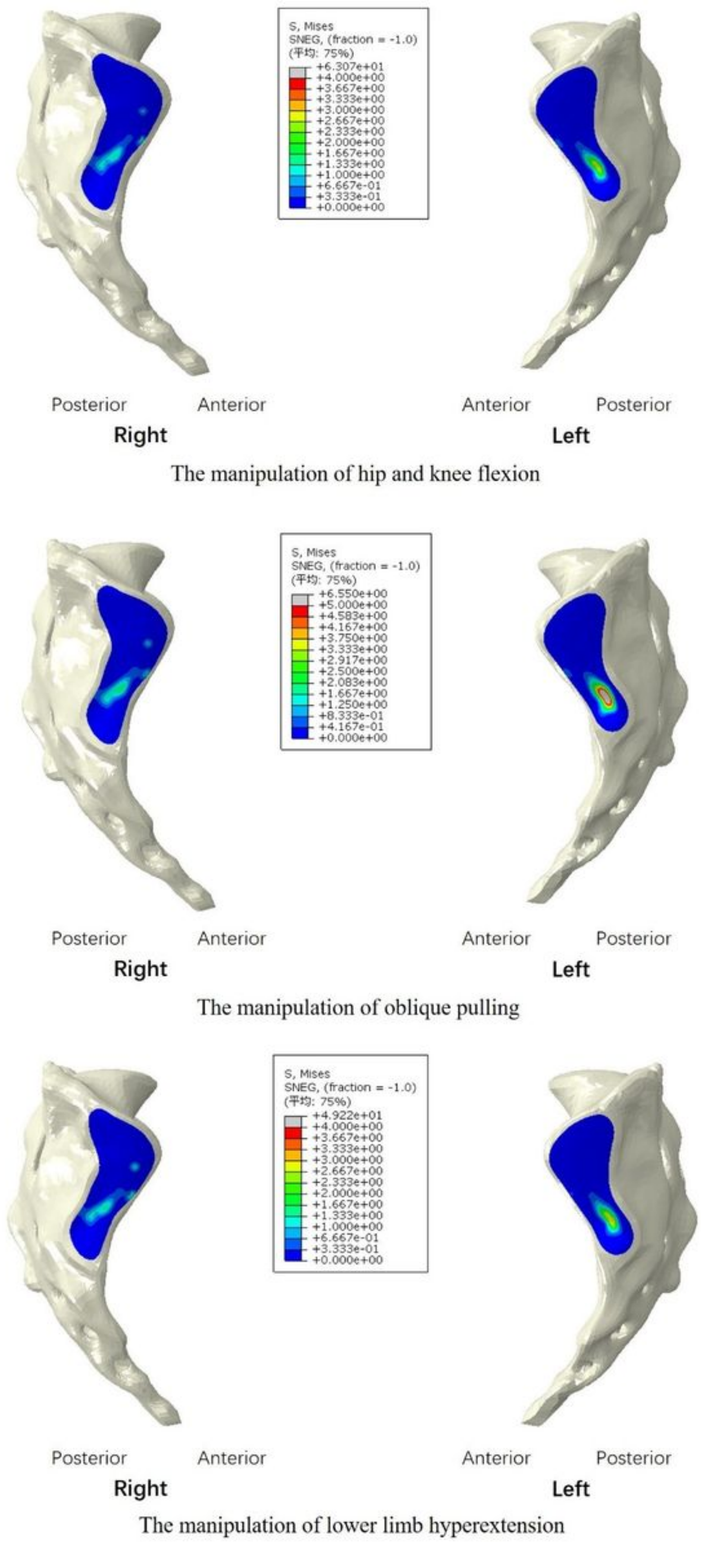

Figure 3

Distribution of sacroiliac joint contact pressure on the sacrum for the three manipulations.

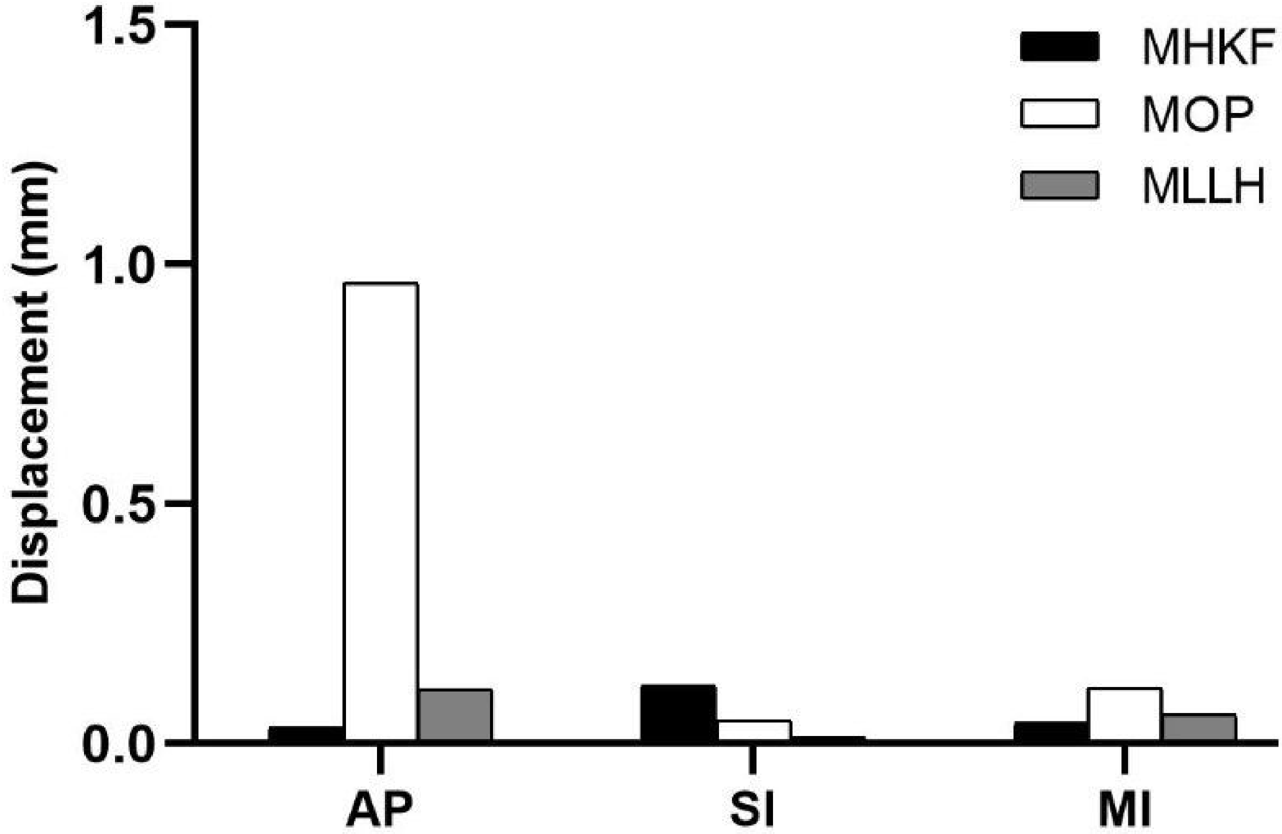

Figure 4

Sacroiliac joint displacements for the three manipulations. MHKF: The manipulation of hip and knee flexion; MOP: The manipulation of oblique pulling; MLLH: The manipulation of lower limb hyperextension. AP: Anterior-posterior direction; SI: Superior-inferior direction; MI: Medial-lateral direction.

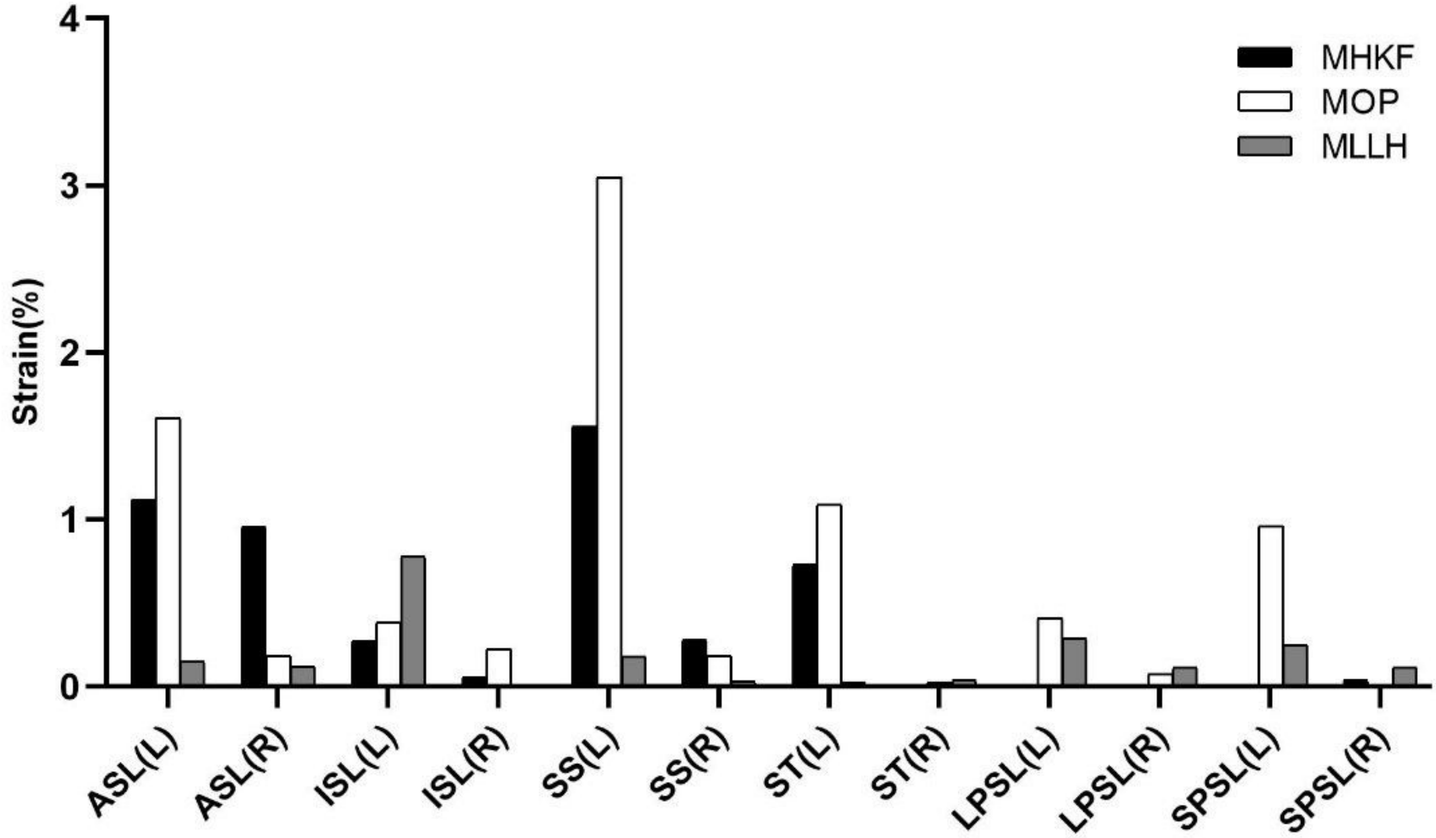

Figure 5

Ligament strains for the three manipulations. MHKF: The manipulation of hip and knee flexion; MOP: The manipulation of oblique pulling; MLLH: The manipulation of lower limb hyperextension; L: Left; R: Right; ASL: Anterior sacroiliac ligament; ISL: Interosseous sacroiliac ligament; SS: Sacrospinous ligament; ST: Sacrotuberous ligament; LPSL: long posterior sacroiliac ligament; SPSL: Short posterior sacroiliac ligament.