Effects of Manipulations of Oblique Pulling on the Biomechanics of the Sacroiliac Joint: A Cadaver Study

Zhun Xu

Department of Spine Surgery, The First Affiliated Hospital of University of South China

Zhiping Huang

Division of Spine Surgery, Department of Orthopaedics, Nanfang Hospital, Southern Medical University

Zhaocong Zhang

School of Traditional Chinese Medicine, Southern Medical University

Ziyu Feng

School of Traditional Chinese Medicine, Southern Medical University

Yiguo Yan

Department of Spine Surgery, The First Affiliated Hospital of University of South China

Qingan Zhu

Division of Spine Surgery, Department of Orthopaedics, Nanfang Hospital, Southern Medical University

Yikai Li (✉ lyk_doc@163.com)

School of Traditional Chinese Medicine, Southern Medical University

Research Article

Keywords:

Posted Date: February 7th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1286795/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

At present, there are many clinical reports on the treatment of sacroiliac joint (SIJ) dysfunction by manipulation of oblique-pulling (MOP). However, the specific mechanism of MOP on the SIJ remains unclear. This study aimed to investigate the effect of MOP on the biomechanics of SIJ and the effect of the anterior sacroiliac ligament (ASL) on the stability of sacroiliac joint. Firstly, nine cadaveric pelvises were applied by MOP-F1 and MOP-F2. Then, segmental ASL resection and SIJ fixation were performed. The range of motion of SIJ were observed in all procedures. Under MOP-F1 and F2, the average total angles were 0.84° and 1.52° , and the displacements were 0.61 mm and 0.98 mm, respectively. Compared with MOP-F1, MOP-F2 caused greater obviously rotation angles and displacements of SIJ. In addition, SIJ mobility significantly increased after complete resection of ASL. The increase was mainly due to the transection of the upper part of ASL. Conclusively, MOP-F2 caused greater rotation angles and displacements of SIJ and it was a more effective manipulation. The ASL played an important role in maintaining the stability of the SIJ, and the upper part of ASL contributed more to the stability.

Introduction

The sacroiliac joint (SIJ) is the largest axial joint in the human body and transmits the weight of upper body to lower limbs¹⁻³. The SIJ is made up of synovium part and ligament part, so it's an amphiarthrodial joint^{4,5}. Clinically, low back pain induced by slight movement of SIJ is called SIJ dysfunction, accounting for about 14.5-22.5%⁶.

Manipulation is a common therapy for SIJ dysfunction⁷⁻¹⁰. At present, there are many clinical reports on the treatment of SIJ dysfunction by manipulation of oblique-pulling (MOP)¹¹⁻¹³, but there are few studies about the mechanism of manipulation. Some researchers^{14,15} believed that MOP could cause ilium rotation and enlarge joint space, which might be the reason for pain relief. However, some authors^{16,17} thought that SIJ not only had a firm wedge-shaped bone structure, but also had strong ligaments around it, so it was very stable. It was difficult for manipulation to pull the dislocated SIJ back. Manipulation might relieve pain by relieving ligament spasms around the joint. Therefore, it is not clear whether MOP can pull back the dislocated SIJ and what the specific mechanism of MOP is. In addition, therapists often apply manipulation based on their own experience. There is no unified standard for MOP. It is also unknown whether different directions of manipulative force can produce different biomechanical effects.

The ligaments perform a vital role in maintaining the stability of SIJ¹⁸⁻²¹. The ligaments surrounding SIJ include anterior sacroiliac ligament (ASL), long posterior sacroiliac ligament (LPSSL), short posterior sacroiliac ligament (SPSSL), interosseous sacroiliac ligament (ISL), sacrospinous ligament (SS), and sacrotuberous ligament (ST). A finite element study found that reducing the stiffness of ligaments could significantly increase the range of motion (ROM) of SIJ and increase the stress on the joint surface. During flexion, extension, and axial rotation of SIJ, the strains of the ISL, ASL and SS were the largest²².

When the SIJ was applied with rotational torque on the sagittal plane, the iliolumbar ligament could obviously constrain the SIJ motion, and the ventral band had the greatest effect on SIJ motion²³. However, the effect of the ASL on the stability of SIJ under MOP has not been studied.

Thus, this study aims to explore the relative displacement and rotation angle of SIJ under MOPs in two loading directions, and the effect of each part of the ASL on the stability of SIJ based on a cadaveric biomechanical experiment.

Results

Rotation angles of intact SIJ under MOP-F1 and F2

Under MOP-F1 and F2, the rotation angle of SIJ surface gradually increased with the increase of loading force. The average total angles were 0.84° and 1.52°, respectively. There was significant difference between the two MOPs for total angle ($t=-6.34$, $p=0.00$). The average rotation angle on a vertical axis of pelvis was the largest among the three directions. Compared with MOP-F1, MOP-F2 caused greater rotation angles of SIJ surface on coronal and vertical axes, and the differences were statistically significant ($t=-2.46$, $p=0.04$; $t=-5.27$, $p=0.00$) (Figure 3). The average angles in each direction are summarized in Table 1.

Displacements of intact SIJ under MOP-F1 and F2

Under MOP-F1 and F2, the displacement of SIJ surface gradually increased with the increase of loading force. The average total displacements were 0.61 mm and 0.98 mm, respectively. There was significant difference between the two MOPs for total displacement ($t=-3.87$, $p=0.01$). The average displacement on a coronal axis of pelvis was the largest among the three directions. Compared with MOP-F1, MOP-F2 caused a greater displacement on a sagittal axis, and the difference was statistically significant ($t=-4.13$, $p=0.01$) (Figure 1). The displacements in each direction are summarized in Table 1.

Table 1. The data of average angle and displacement of the sacroiliac joints produced by MOP-F1 and F2 applying to hemi-pelvises.

	MOP-F1	MOP-F2
Rx (°)	0.37±0.22	0.56±0.38
Ry (°)	0.58±0.51	1.25±0.75
Rz (°)	0.46±0.28	0.58±0.28
Tx (mm)	0.44±0.50	0.74±0.33
Ty (mm)	0.25±0.15	0.26±0.21
Tz (mm)	0.40±0.19	0.55±0.16
R_total (°)	0.84±0.59	1.52±0.83
T_total (mm)	0.61±0.21	0.98±0.39

Note: Rx represents the angle of rotation on a coronal axis. Ry represents the angle of rotation on a vertical axis. Rz represents the angle of rotation on a sagittal axis. Tx represents the displacement on a coronal axis. Ty represents the displacement on a vertical axis. Tz represents the displacement on a sagittal axis. R_total represents the total rotation angle. T_total represents the total displacement.

Effect of ASL

Only six specimens were included in the SIJ stability test. The rotation angles of SIJ were 1.17° and 3.17° in the state of intact ASL and resected ASL, respectively. The displacements of SIJ were 0.88 mm and 3.02 mm, respectively. Both rotation angle and displacement of SIJ in the state of resected ASL were significantly larger than that of the intact ASL ($t=-5.30$, $p=0.01$; $t=-4.08$, $p=0.02$) (Figure 2).

Effect of the two parts of ASL

In group 1, in the state of intact, the upper part resection and complete resection of ASL, the rotation angles of SIJ were 1.45°, 2.47° and 3.01°, and the displacements were 0.99 mm, 1.83 mm and 3.30 mm, respectively. The differences were not statistically significant among the three states for the rotation angle and displacement. In group 2, in the state of intact, lower part resection and complete resection of ASL, the rotation angles of SIJ were 0.89°, 1.50° and 3.27°, and the displacements were 0.72 mm, 1.17 mm and 2.73 mm, respectively. There were significant differences between the states of lower part resection and complete resection for the rotation angle and displacement ($t=-5.69$, $p=0.03$; $t=-7.06$, $p=0.02$) (Figure 3).

Effect of SIJ Fixation

In the state of ASL resection and SIJ screw fixation, the rotation angles of SIJ were 3.17° and 1.66°, and the displacements of SIJ were 3.02 mm and 1.29 mm respectively. SIJ fixation reduced the range of SIJ motion obviously, but there were no statistical differences between the two states. In addition, there were

no significant differences between the state of intact ASL and SIJ fixation for rotation angle and displacement of SIJ (Figure 2).

Discussion

SIJ dysfunction is a common disease that affects 90% of adults throughout their lives¹. The disease seriously interferes people's work and life. Manipulation has the advantages of minimal invasion and good curative effect, and it is widely used in clinical practice. However, the biomechanical mechanism of manipulation remains unclear. Clarifying its mechanism helps to improve the effect of manipulation, which is of great significance to the treatment of SIJ disorders.

Miller et al.²⁴ studied the correlation between loading force and displacement of SIJ using eight specimens. By fixing the bilateral ilium, they applied 294N forces from the upper, lower, anterior, posterior, and middle sides and 42Nm torques of flexion, extension, lateral flexion, and rotation to the sacrum. The average SIJ displacements were 0.28 mm, 0.26 mm, 0.48 mm, 0.53 mm and 0.01 mm, and the average rotation angles were 1.31°, 1.94°, 0.37° and 0.80°. Lindsey and colleagues²⁵ performed a cadaveric study to investigate the motion of SIJ, and found under the loading condition of flexion-extension, rotation and lateral flexion, the ROM of SIJ were 1.94° and 2.65°, 1.20° and 1.77°, 0.36° and 1.16° in the state of single and double leg stance. In this experiment, nine hemi-pelvic specimens were used to study the effects of MOPs in different directions on the SIJ. The results showed that, under 100N loading force, the total rotation angles of F1 and F2 were 0.84° and 1.52°, and the displacements were 0.61 mm and 0.98 mm, respectively. The ROM of SIJ was consistent with previous studies^{24,25}. MOP-F2 could produce a greater rotation angle and displacement of the SIJ, which might be related to the fact that the force direction of MOP-F2 was more perpendicular to the SIJ surface and the torque was greater. Rotation angles on a vertical axis produced by MOP-F1 and F2 were the largest among the three directions. MOPs were applied on the anterior superior iliac spine. The loading force applied from the ventral to the dorsal side caused the ilium to rotate outwardly with respect to the sacrum, so the rotation angle was maximum on the vertical axis. In the three directions, the displacements on a coronal axis caused by MOP-F1 and F2 were the largest, while the displacements on a vertical axis were the smallest. The results suggested that the main effect of MOP was to produce coronal axis movement of the SIJ. In brief, MOP can cause the movement of SIJ, but the ROM is small. The MOP-F2 is a more effective manipulation.

The ligaments perform a vital role in holding the different components of the structure together against loads, which otherwise would cause separation at the pubis and SIJs. Sichting et al.¹⁸ considered that ligaments served as the mechanical stabilization device of the pelvis. Bohme et al.¹⁹ observed that the ASL and ST bore the greatest load in anteroposterior compression pelvic injuries and that the SS played an important role in the vertical stability of the pelvis. Eichenseer et al.²² indicated that the ligaments around the SIJ could restrict its movement and decrease its stress through a finite element study. Abdelfattah and colleague²⁶ found that the pubic symphysis and the ASL played a greater role in maintaining the stability of the pelvis when the pelvis suffered a book-turning violence. In this study, it

was found that after complete resection of the ASL, the displacement of the SIJ increased by 243% and the rotation angle increased by 171%. It also proved that the ASL played an important part in maintaining the stability of the SIJ.

The sacrum is wedge-shaped, tilted from top to bottom and with a concave surface that is closely inserted into the convex surface of the ilium²⁷. Since humans are upright, the lower part of the SIJ surface fits more tightly. In addition, the previous CT imaging study observed that the SIJ space width gradually narrowed from top to bottom. Theoretically, the SIJ gap is wider, the ROM of SIJ is bigger, and the ligaments maintaining SIJ stability bear greater strains. In the anatomical observation of SIJ, we found that there were some differences in anatomical structure between the upper and lower parts of ASL divided by the intersection of arcuate line and SIJ. Therefore, we investigated the upper and lower parts of ASL in maintaining the stability of the SIJ. The results showed that, compared with the intact state of ASL, resecting the upper part, the rotation angle and displacement of the SIJ increased by 70% and 85%, while resecting the lower part, the rotation angle and displacement of the SIJ increased by 69% and 63%. After resecting the upper part, the rotation angle and displacement of the SIJ increased by 22% and 80% by resecting the lower part. After resecting the lower part, the rotation angle and displacement of the SIJ increased by 118% and 133% by resecting the upper part. The data indicated that the upper part of ASL played a more important role in maintaining the stability of the SIJ. The results were consistent with the anatomical characteristics of SIJ.

Sacroiliac screw fixation is a common method in the treatment of SIJ diseases. Lindsey et al.²⁸ carried out some studies to explore the effect of the iFuse System in reducing the flexibility of the SIJ. In an in vitro study on seven human specimens, they found a reduction of the ROM of 41%, 36% and 36% in flexion-extension, lateral bending and axial rotation, respectively. Cross et al.²⁹ argued that under the torque of flexion-extension, lateral flexion, rotation, the rotation angles of SIJ were 2.92° and 1.75°, 1.16° and 0.59°, 1.46° and 1.52° in the state of intact SIJ and fixed SIJ with sacroiliac screw. In this study, after sacroiliac screw fixation, the rotation angle of SIJ reduced by 48%, and the displacement of SIJ reduced by 57%. It could be seen that the ROM of SIJ significantly reduced, which was consistent with the previous studies^{29,30}. The results suggested that sacroiliac screw fixation was an effective method for SIJ fixation. Percutaneous sacroiliac screw fixation is an alternative treatment for patients with SIJ disease who have failed in conservative treatments.

Study Limitations

There are some limitations of this study. First, the pelvic specimens were the hemi-pelvises and the symphysis pubes had been dissected, which affected the stability of the SIJ. To this end, we took the following measures: (1) A smaller loading force of 100N was applied; (2) A steel cable was placed at the symphysis pubis to restrict the movement of the symphysis pubis, and the tension was monitored. The forces caused by MOP-F1 and F2 were 7.62N and 13.85N, about 10% of the loading force. The results indirectly reflected that the movement of the symphysis pubis was small. Thus, the hemi-pelvis

specimens had little effect on the experiment. Second, only six specimens were included in the ASL experiments, so the number of specimens was small. Finally, the simplified MOP in this study could not fully reflect the characteristics of clinical MOP.

Methods

Preparation of specimens

Nine fresh-frozen cadaveric hemi-pelvises (five males, four females, aged 20-60 years) were obtained from the Department of Anatomy in Southern Medical University. This study was approved by the Southern Medical University Nanfang Hospital Medical Ethics Committee. Every donors or next-of-kin signed and informed consent for the use of donors' bodies after donors' death for teaching and research purposes. All trials were performed in accordance with the principles of the Declaration of Helsinki. These specimens were free of fractures, tumors, malformations, or serious osteoporosis. The skin, fat and muscle tissues were removed. Ligaments around SIJ on one side, including ASL, LPSL, SPSL, ISL, SS and ST, were all maintained on the specimens.

Pelvis fixation and loading points

The middle part of sacrum was embedded in plaster and the hemi-pelvis was placed in a standard position, that was, the symphysis pubis and the bilateral anterior superior iliac spine were positioned in the standard sagittal plane.

The hemi-pelvis specimen with plaster embedded was fixed in supine position on an adjustable angle fixture. The loading points were on the anterior superior iliac spine (ASIS). The soft tissue around ASIS was removed as cleanly as possible. The screw track was preformed by hand electric drill and strengthened by denture base resin solution. A screw (25*3.5mm) was inserted into ASIS through the screw track immediately and the direction of screw was perpendicular to the sagittal plane of pelvis. The loading point 1 was achieved. Then, the hemi-pelvis rotated 30° along the vertical axis through fixture rotation. In the same way, a screw was inserted at the ASIS and perpendicular to the platform for the preparation of loading point 2. Finally, the denture base resin solution was used to embed screw and the loading point was molded into a ball and socket shape, so as to connect the ball head of loading rod. The above procedures were mainly to increase the stability of junction between the loading rod and the loading point.

Preparation for test

The hemi-pelvis and fixture were fixed on a horizontal platform that could be moved in four directions. By moving the position of platform, the loading point could match the ball head of the loading rod. Considering the poor stability of SIJ in hemi-pelvis state, a steel cable was placed at the pubic symphysis and fixed to a stationary platform. In addition, a force sensor was attached to the cable to monitor the tension on the pubic symphysis. Optical motion tracking markers were placed on both sides of SIJ.

Finally, the motion data from point B on the SIJ (the intersection of arcuate line and SIJ) were captured by NDI Optotrak Certus.

Biomechanical test

Firstly, the specimens were tested for MOPs in two directions in their intact state, and then tested for SIJ stability.

The nine specimens were applied randomly by MOP-F1 and F2. In MOP-F1, the direction of manipulative force was at a degree of 30 to the sagittal plane of the pelvis. In MOP-F2, the direction of manipulative force was parallel to the sagittal plane of the pelvis (Figure 4).

The detailed procedures were as follows:

The procedure of MOP-F1: The hemi-pelvis was placed at a degree of 30 to the sagittal plane of pelvis. The ball head was combined with the loading point 2. A force of 10N was pre-applied to make the ball head fully contact the loading point. Then a vertical downward load of 10~100N was applied with a loading frequency of 0.025Hz. After the loading force reached 100N, it was gradually unloaded to 10N. Then the next cycle was repeated. The loading was cyclic three times for each specimen, and the data from the third cycle were taken as experimental data.

The procedure of MOP-F2: The hemi-pelvis was placed at a supine position. The ball head was combined with the loading point 1. The loading mode was the same as MOP-F1.

The procedure of stability of SIJ: After the MOP-F1 and F2 tests, the tests of stability of SIJ were continued. The ASL was divided into two parts (upper and lower) by the intersection of the arcuate line and the SIJ. The six hemi-pelvises were divided into two groups randomly. In group 1, the upper part of ASL was resected followed by the lower part. In group 2, the lower part of ASL was resected followed by the upper part. Finally, The SIJ was fixed with two SIJ screws (6.5*75mm). The loading mode was the same as MOP-F2 (Figure 5).

Statistical analysis

Statistical analysis was performed using SPSS version 20.0 software (IBM SPSS Statistics for Windows, Armonk, NY, USA). Data are presented as $X \pm s$. The paired t-test was used to evaluate the differences in displacement and rotation angle of SIJ between MOP-F1 and F2. In addition, the paired t-test was used to evaluate the contributions of each part of ASL within each group, the differences between the state of intact SIJ and ASL resection, and the differences between the state of intact SIJ and SIJ fixation. The Mann-Whitney U test was used to compare the two parts of ASL contributions between the two groups. A p value < 0.05 indicated a statistically significant difference.

Conclusions

This novel study was the first to investigate the biomechanical mechanism of MOP on SIJ with human pelvis specimens, and clarify the effect of different loading directions of MOP on the movement of SIJ. In addition, this study confirmed that the ASL played an important role in maintaining the stability of the SIJ, and proved that the upper part of ASL contributed more to the stability.

Declarations

Data availability

The datasets used and/or analyzed during the current study are not publicly available due to the continuity of the subject but are available from the corresponding author upon reasonable request.

Acknowledgements

We sincerely thank the staff of the Spine and Spinal cord Injury Laboratory of Nanfang Hospital for providing assistance for this study.

Author contributions

Z.X., Z.H., Z.Z., and Z.F. carried out the cadaveric experiment. Y.L., Q.Z., and Y.Y. participated in the study design and discussion. All of the authors read and approved the final manuscript.

Funding

This work was supported by Sanming Project of Medicine in Shenzhen (grant number SZZYSM202108013), Innovation Team and Talents Cultivation Program of National Administration of Traditional Chinese Medicine (grant number ZYYCXTD-C-202003) and the National Natural Science Foundation of China (grant number 81972110).

Competing interests

The authors declare no competing interests.

References

1. Joukar, A. *et al.* Sex Specific Sacroiliac Joint Biomechanics During Standing Upright: A Finite Element Study. *Spine*. **43**, e1053-e1060. (2018)
2. Wu, T. *et al.* Biomechanical study of three kinds of internal fixation for the treatment of sacroiliac joint disruption using biomechanical test and finite element analysis. *J Orthop Surg Res*. **13**, 152. (2018)
3. Cohen, S.P., Chen, Y. & Neufeld, N.J. Sacroiliac joint pain: a comprehensive review of anatomy, diagnosis, and treatment. *Anesthesia And Analgesia*. **101**, 1440–1453. (2005)

4. Al-Subahi, M. *et al.* The effectiveness of physiotherapy interventions for sacroiliac joint dysfunction: a systematic review. *J Phys Ther Sci.* **29**, 1689-1694. (2017)
5. Yang, X.W., Chen, Z.J., Zhang, S.Q., Zhang, M.C. & Li, Y.K. A three-dimensional finite element analysis of sacroiliac joint exerted simulating oblique-pulling manipulation. *J Pract Med.* **30**, 2228–2230. (2014)
6. Xu, Z. *et al.* A finite element analysis of sacroiliac joint displacements and ligament strains in response to three manipulations. *BMC Musculoskeletal Disorders.* **21**, 709. (2020)
7. Nejati, P., Safarcherati, A. & Karimi, F. Effectiveness of exercise therapy and manipulation on sacroiliac joint dysfunction: a randomized controlled trial. *Pain Physician.* **22**, 53-61. (2019)
8. Kamali, F., Zamanlou, M., Ghanbari, A., Alipour, A. & Bervis, S. Comparison of manipulation and stabilization exercises in patients with sacroiliac joint dysfunction patients: a randomized clinical trial. *J Bodyw Mov Ther.* **23**, 177-182. (2019)
9. Farazdaghi, MR. *et al.* Effect of sacroiliac manipulation on postural sway in quiet standing: a randomized controlled trial. *Braz J Phys Ther.* **22**, 120-126. (2018)
10. García-Peñalver, U., Palop-Montoro, M. & Manzano-Sánchez, D. Effectiveness of the muscle energy technique versus osteopathic manipulation in the treatment of sacroiliac joint dysfunction in athletes. *Int J Environ Res Public Health.* **17**, 4490. (2020)
11. Wang, R.Z., Zhao, X., & Yu, H.C. Manipulation of oblique pulling treatment of sacroiliac joint dislocation. *Modern Traditional Chinese Medicine.* **33**, 77-78. (2013)
12. Yang, Y.Z., Gan, Y.J., Zheng, Z.Z. Clinical observation on the treatment of sacroiliac joint dislocation by massage and improved manipulation of oblique pulling. *Chinese Manipulation & Rehabilitation Medicine.* **9**, 12-14. (2018)
13. Fan, Z.Y. & Wu, S. Based on the theory of "bone dislocation, tendon grooving", discussing the characteristics of Lin's manipulation in the treatment of sacroiliac joint dysfunction. *J Trad Chin Orthop Trauma.* **33**, 47-49. (2021)
14. Dang, Y.F. Clinical observation on the treatment of sacroiliac joint dislocation by manipulation of hip and knee flexion. *Shaanxi J Tradit Chin Med.* **33**, 440-441. (2012)
15. Luan, M.Y., Luan, M.Y., Wang, C. & Xue, W. The characteristics of Luan's manipulation in the treatment of sacroiliac joint dysfunction. *LiaoNing J Tradit Chin Med.* **29**, 462-463. (2002)
16. Tullberg, T., Blomberg, S., Branth, B. & Johnsson, R. Manipulation does not alter the position of the sacroiliac joint. a roentgen stereophotogrammetric analysis. *Spine.* **23**, 1124–1128; discussion 1129. (1998)
17. Wang, X.C., Xiao, H.E., & Wang, X.B. 132 cases of sacroiliac joint dislocation treated by three-step combined manipulation. *Chinese Journal of Traditional Medical Traumatology & Orthopedics.* **19**, 40-41. (2011)
18. Sichting, F. *et al.* Pelvic belt effects on sacroiliac joint ligaments: a computational approach to understand therapeutic effects of pelvic belts. *Pain Physician.* **17**, 43-51. (2014)

19. Bohme, J. *et al.* The extent of ligament injury and its influence on pelvic stability following type II anteroposterior compression pelvic injuries—a computer study to gain insight into open book trauma. *J Orthop Res.* **32**, 873-879. (2014)
20. Hammer, N. *et al.* Ligamentous influence in pelvic load distribution. *The Spine Journal.* **13**, 1321–1330. (2013)
21. Phillips, A.T., Pankaj, P., Howie, C.R., Usmani, A.S. & Simpson, A.H. Finite element modelling of the pelvis: inclusion of muscular and ligamentous boundary conditions. *Medical Engineering & Physics.* **29**, 739-748. (2007)
22. Eichenseer, P.H., Sybert, D.R. & Cotton, J.R. A finite element analysis of sacroiliac joint ligaments in response to different loading conditions. *Spine.* **36**, e1446-1452. (2011)
23. Pool-Goudzwaard, A. *et al.* The iliolumbar ligament: its influence on stability of the sacroiliac joint. *Clinical Biomechanics* (Bristol, Avon). **18**, 99-105. (2003)
24. Miller, J.A., Schultz, A.B. & Andersson, G.B. Load-displacement behavior of sacroiliac joints. *J Orthop Res.* **5**, 92-101. (1987)
25. Lindsey, D.P. *et al.* Biomechanics of unilateral and bilateral sacroiliac joint stabilization: laboratory investigation. *J Neurosurg Spine.* **28**, 326-332. (2018)
26. Abdelfattah, A. & Moed, B.R. Ligamentous contributions to pelvic stability in a rotationally unstable open-book injury: a cadaver study. *Injury.* **45**, 1599-1603. (2014)
27. Shi, D., Wang, F., Wang, D., Li, X. & Wang, Q. 3-D finite element analysis of the influence of synovial condition in sacroiliac joint on the load transmission in human pelvic system. *Med Eng Phys.* **36**, 745–753. (2014)
28. Soriano-Baron, H. *et al.* The effect of implant placement on sacroiliac joint range of motion: posterior versus transarticular. *Spine.* **40**, e525-530. (2015)
29. Cross, W.W. *et al.* In vitro biomechanical evaluation of a novel, minimally invasive, sacroiliac joint fixation device. *Int J Spine Surg.* **12**, 587-594. (2018)

Figures

Figure 1

The MOP-F1 and F2 applying to hemi-pelvises produced the rotation angle (left) and displacements (right) of SIJ. Rx represents the angle of rotation on a coronal axis. Ry represents the angle of rotation on a vertical axis. Rz represents the angle of rotation on a sagittal axis. R_total represents the total rotation angle. Tx represents the displacement on a coronal axis. Ty represents the displacement on a vertical axis. Tz represents the displacement on a sagittal axis. T_total represents the total displacement. The symbol “*” indicates that there is a statistical difference between two groups, that is, $P \leq 0.05$. MOP: Manipulation of oblique-pulling. SIJ: Sacroiliac joint.

Figure 2

The images show that the rotation angle (left) and displacement (right) of SIJ under the states of the intact ligament, ASL resection and SIJ fixation. R_int and T_int represent the rotation angle and displacement under the state of intact ligament. R_sec and T_sec represent the rotation angle and

displacement under the state of ASL resection. R_fix and T_fix represent the rotation angle and displacement under the state of SIJ fixation. ASL: Anterior sacroiliac ligament. SIJ: Sacroiliac joint.

Figure 3

Flow diagram showing the study design with the associated statistical result at each stage of ASL resection of two parts. There was no significant change within groups after sectioning of the lower part of

ASL whether this was performed before or after the upper part of ASL sectioning. In addition, there was no significantly difference between groups after sectioning of the upper part of ASL whether this was performed before or after sectioning of the lower part of ASL. "T" represents displacement. "R" represents rotation angle. ASL: Anterior sacroiliac ligament. SIJ: Sacroiliac joint.

Figure 4

MOP-F1 (left) and MOP-F2 (right) applied to the hemi-pelvis specimen. MOP: Manipulation of oblique-pulling.

Figure 5

The left image showed the upper part and lower part of ASL. The B point was the cutoff point between the upper and lower parts of ASL. The right image showed two SIJ screws were used to fix the SIJ. ASL: Anterior sacroiliac ligament. SIJ: Sacroiliac joint.