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Experimental Study

Pelvic Belt Effects on Sacroiliac Joint Ligaments: A Computational Approach to Understand Therapeutic Effects of Pelvic Belts

Freddy Sichting, MSc[1], Jerome Rossol, BSc[2], Odette Soisson, MD[2], Stefan Klima, MD[1], Thomas Milani, PhD[1], and Niels Hammer, MD[2]

From: Technische Universitat Chemnitz, Germany; University of Leipzig, Germany.

Sichting is with the Department of Human Locomotion, Technische Universität Chemnitz, Chemnitz, German. Rossol, is with theInstitute of Anatomy, University of Leipzig, Leipzig, Germany. Dr. Soisson is with the Institute of Anatomy, University of Leipzig, Leipzig, Germany. Dr. Klima is with the Trauma Surgery, University of Leipzig, Leipzig, Germany. Dr. Milani is with the Department of Human Locomotion, Technische Universität Chemnitz, Chemnitz, Germany. Dr. Hammer is with the Institute of Anatomy, University of Leipzig, Leipzig, Germany

Address Correspondence:
Freddy Sichting, MSc
Department of Human Locomotion, Technische Universität Chemnitz,
Thüringer Weg 11, 09126
Chemnitz, Germany
E-Mail: freddy.sichting@hsw.tu-chemnitz.de

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Background: The sacroiliac joint is a widely described source of low back pain. Therapeutic approaches to relieve pain include the application of pelvic belts. However, the effects of pelvic belts on sacroiliac joint ligaments as potential pain generators are mostly unknown.

Objectives: The aim of our study was to analyze the influence of pelvic belts on ligament load by means of a computer model.

Study Design: Experimental computer study using a finite element method.

Methods: A computer model of the human pelvis was created, comprising bones, ligaments, and cartilage. Detailed geometries, material properties of ligaments, and in-vivo pressure distribution patterns of a pelvic belt were implemented. The effects of pelvic belts on ligament strain were computed in the double-leg stance.

Results: Pelvic belts increase sacroiliac joint motion around the sagittal axis but decrease motion around the transverse axis. With pelvic belt application, most of the strained sacroiliac joint ligaments were relieved, especially the sacrospinous, sacrotuberous, and the interosseous sacroiliac ligaments. Sacroiliac joint motion and ligament strains were minute. These results agree with validation data from other studies.

Limitations: Assigning homogenous and linear material properties and excluding muscle forces are clear simplifications of the complex reality.

Conclusions: Pelvic belts alter sacroiliac joint motion and provide partial relief of ligament strain that is subjectively marked, although minimal in absolute terms. These findings confirm theories that besides being mechanical stabilizers, the sacroiliac joint ligaments are likely involved in neuromuscular feedback mechanisms. The results from our computer model help with unraveling the therapeutic mechanisms of pelvic belts.

Key words: Finite element computer study, low back pain, neuromuscular feedback, pelvic biomechanics, pelvic belt intervention, sacroiliac joint ligaments, sacroiliac joint motion

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The sacroiliac joint (SIJ) is regarded as a potential, but underestimated, source of low back pain (1-5), affecting 15% to 30% of individuals with chronic non-radicular pain (6-10). However, altered pelvic biomechanics that cause sacroiliac dysfunction and the involved anatomical structure are poorly understood and subject to ongoing debates (11-13). One explanation may be the extensive network of strong ligaments and their role in SIJ control. The ligaments maintain the integrity of the joint and are also involved with limiting the extent of SIJ motion (14,15). In numerous studies the ligaments are regarded as mechanical stabilizers (16-20). Recent studies hypothesize that the ligaments may be involved in sensory-motor control (18,21-25). These theories of ligament function are based on anatomical examinations and SIJ motion analysis. However, the aforementioned studies lack details on the loads transferred to the ligaments in SIJ motion.

Taking into account data on SIJ rotation of 2 to 4 degrees in body donors (26-28), Buford and coworkers (29) showed that this range of motion is potentially beyond the limits of physiological loading. Consequently, the ligaments could serve as potential pain generators, considering the nociceptive elements located inside the SIJ and the ligaments (30-33).

One strategy of conservative treatment of SIJ dysfunction is the use of pelvic belts (21). Recent studies determined the influence of pelvic compression on stability (20,34,35) and motor control (22,36). The described SIJ motion-reducing effects of pelvic belts led to the proposal that pelvic belts are also capable of relieving loaded ligaments. As yet, only one study has examined the influence of pelvic belts on ligament forces (37). Here, the simulation of pelvic belt effects revealed an unloading of the sacrotuberous ligaments, but also a loading of the sacrospinous ligaments. More data will help to understand how the ligaments are strained during pelvic belt application.

This study analyzes SIJ motion and ligament strain levels with and without pelvic belt application. A pelvic computer model was developed that comprises detailed bony, ligamentous, and cartilaginous structures. We hypothesize that pelvic belts alter SIJ motion such that the most loaded ligaments are relieved. This could be a potential explanation for ligament-related pain reducing effects of pelvic belts.

METHODS

Geometry Creation

A finite element model of a pelvic ring of one male subject (29 years, body height 185 cm, body weight 69 kg) was established from computed tomography (Somatom® Volume ZoomScanner, Siemens AG, Erlangen, Germany; slice thickness = 0.5 mm, 777 slices). AMIRA 3.1.1 (VSG, Burlington, MA, USA) was used for semiautomatic segmentation of the bony geometries of the sacrum and both ilia, as well as the fifth lumbar vertebra and the cranial ends of both femora. The raw geometric data of all bones were then converted into so-called solid parts. Next, the single solid parts were assembled into a complete bony pelvis model by means of Geomagic software solutions (Geomagic, Morrisville, NC, USA). The gaps between the symphysis, the femora and the acetabulum, and the ventral portion of the SIJ were fused together by solid parts and defined as cartilage tissue. Finally, the assembly was imported into ANSYS Workbench (ANSYS, Inc., Canonsburg, PA, USA; Fig. 1). A total number of 210 spring elements

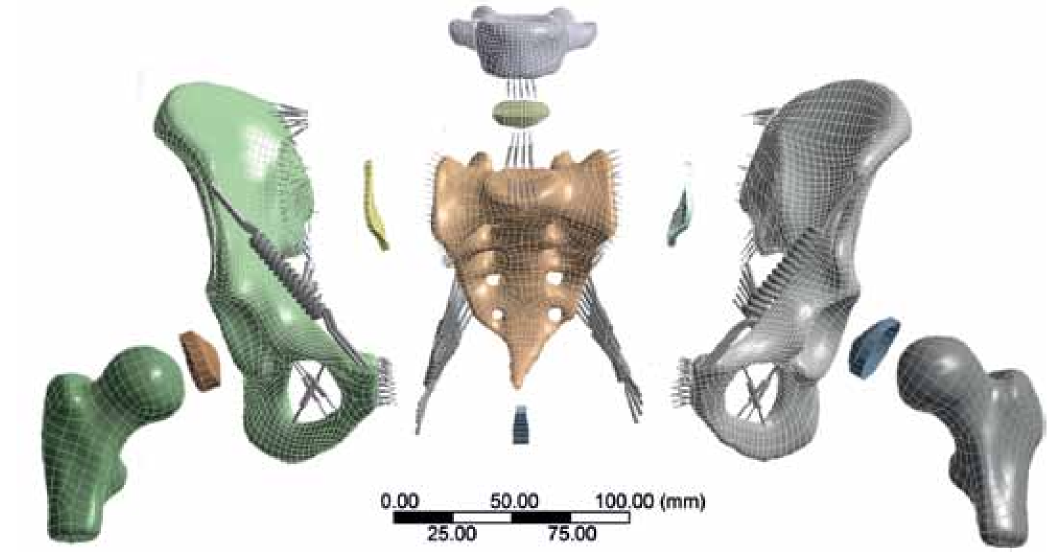

Fig. 1. *Assembly drawing of the finite element model in the frontal view. The pelvic model consisted of detailed geometries from a computed tomography dataset of one healthy 29-year-old male and the ligament data on the basis of previous studies on the iliotibial tract. Both coxal bones, the sacrum and coccyx, the fifth lumbar vertebra, the proximal ends of both femora, and the connecting joint surfaces were integrated. A total of 210 spring elements represented the general fiber alignment of the sacroiliac joint ligaments.*

were integrated, representing the ligaments and the obturator membrane. The number of spring elements representing each ligament is found in Table 1. All ligaments were modeled as a collection of truss elements, which exhibit stiffness only in tension and no resistance to compression force. The anatomical orientations and the mean cross sectional areas of the ligaments were chosen based on our own investigations (38-40).

Mesh Generation

All modeled bones were meshed with tetrahedral elements to create solid meshes. Mesh refinement studies were performed to reach optimal element size. The refinement was defined to be completed when a change in element size caused a maximum change of 5% in the analytical solutions (41). The final finite element model contained 151,642 nodes and 87,233 elements. The mean *element quality,* providing a composite quality metric that ranges between 0 and 1, was given as 0.75, indicating a good mesh quality.

Material Properties

The mechanical behavior of all tissues was simplified and represented as homogeneous, isotropic, and linearly elastic. Bony and cartilaginous element properties were chosen in accordance with previous pelvic models (42) and baseline material properties of ligaments were selected from our own studies of iliotibial tract specimens (43,44). Table 2 provides detailed information about the material properties and number of elements of all tissues used for the finite element model.

Boundary Conditions

To investigate the influence of a pelvic belt on SIJ motion and associated ligament strain during double-leg stance, we applied the following boundary conditions: First, we fixed an area (960 mm^2) of the ventral surface of sacrum between the first and second sacral vertebra. To simulate the double-leg stance position, an axial compressive force of 250 N was applied to the sacral promontory, and another axial compressive force of 250 N was applied to both femora (125 N each). Additionally, in-vivo pressure distribution measurements (pedar system, novel GmbH, Munich, Germany) were performed on one healthy male person (age 26 years, body height 190 cm, body weight 80 kg; Fig. 2A and B). These data were integrated into the finite element model to simulate the compression effect of the pelvic belt (SacroLoc, Bauerfeind AG, Zeulenroda-Triebes, Germany).

Data Analysis and Validation

SIJ motion was determined by measuring the displacement of defined marks on the sacrum and the

Table 1. *Sacroiliac joint ligament strain behavior of the initial double-leg stance scenario is compared to the application of a pelvic belt.*

Ligament	Number of Spring Elements	Loading Scenario without Pelvic Belt		Loading Scenario with Pelvic Belt			
		Strained	Slackened	Remained Strained	Strained to Slackened	Slackened to Strained	Remained Slackened
ASL	26	3 (0.00 to 0.03%)	23 (-0.22 to -0.01%)	3 (0.05 to 0.09%)	0	2 (0.02 to 0.04%)	21 (-0.27 to -0.01%)
ISL	15	6 (0.00 to 0.12%)	9 (-0.14 to -0.02%)	3 (0.00 to 0.09%)	3 (-0.14 to -0.06%)	1 (0.00%)	8 (-0.37 to -0.05%)
PSL	20	16 (0.00 to 0.22%)	4 (-0.26 to -0.03%)	12 (0.03 to 0.32%)	4 (-0.06 to -0.02%)	4 (0.01 to 0.30%)	0
LPSL	4	0	4 (-0.14 to -0.01%)	0	0	2 (0.01 to 0.03%)	2 (-0.08 to -0.03%)
SS	4	4 (0.06 to 0.08%)	0	4 (0.05 to 0.06%)	0	0	0
ST	5	5 (0.03 to 0.07%)	0	5 (0.02 to 0.06%)	0	0	0
ILL	9	3 (0.01 to 0.04%)	6 (-0.10 to -0.02%)	0	3 (-0.15 to -0.05%)	0	6 (-0.14 to -0.03%)

The total number of spring elements representing each one of the ligaments is given. Ligament strain behavior is presented as the number of spring elements being strained or slackened. Strained refers to a positive elongation, whereas a negative elongation is referred to as slackening. Respective strain levels are quoted in parentheses. ASL = anterior, ISL = interosseous, PSL = posterior, LPSL = long posterior sacroiliac ligament, SS = sacrospinous, ST = sacrotuberous, ILL = iliolumbar ligament.

Table 2. *Homogenous and linear material properties were assigned to the ligaments and the bones of the pelvis.*

Tissue	Number of Elements	Young's Modulus (MPa)	Poisson's Ratio
Bone		**11 000**	**0.3**
Sacrum	16 262		
Left ilium	15 244		
Right ilium	14 204		
5th lumbar vertebra	8 612		
Left femur	2 870		
Right femur	2 799		
Cartilage		**150**	**0.3**
Left articular surface	3 222		
Right articular surface	3 149		
Intervertebral disc	4 402		
Pubic symphysis	1 673		
Left femur	6 315		
Right femur	8 481		
Ligament	**210**	**350**	**-**

Young's modulus, as a measure of stiffness, represents the ratio of stress to strain under an elastic deformation. Poisson's ratio, as a measure of elasticity, describes the ratio of transverse strain to axial strain. The number of elements and material properties are given for each of the modeled structures.

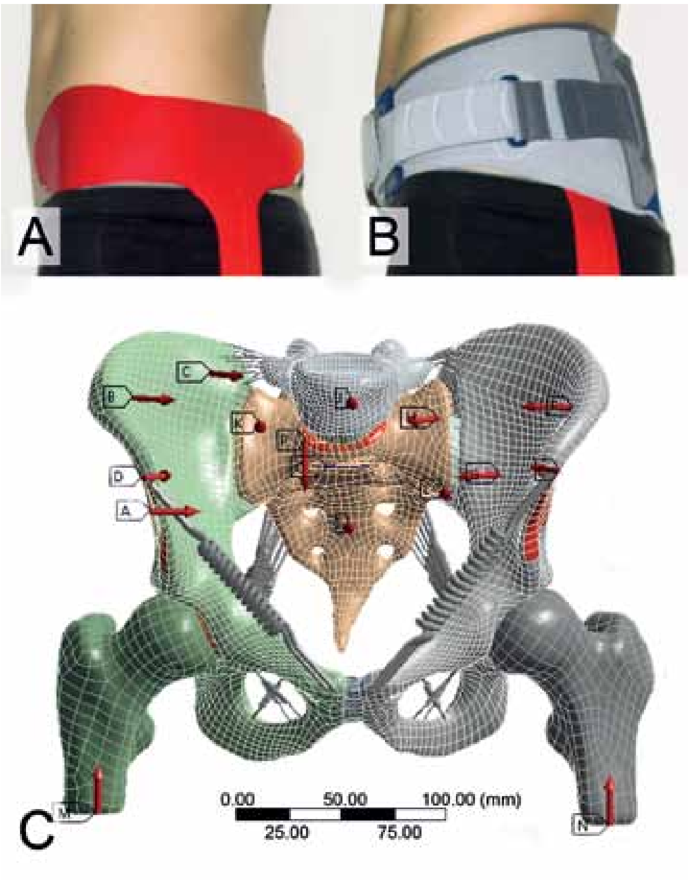

Fig. 2. *The data on pelvic compression was recorded in one healthy 26 year-old male by means of a pressure measuring system. (A) and (B) show the in-vivo setup in the volunteer. (C) depicts the resultant force vectors that were added to the computer model as boundary conditions to simulate the pelvic belt effects.*

right ilium referring to the goniometric method described by Vleeming et al (45). The strain level of each ligament was then calculated. The term "strain" will be used to describe a positive strain level, whereas a negative strain level will be referred to as "slackening." The numeric model was validated indirectly using the data from Varga et al (46) and Buford et al (29). Both studies fulfilled our requirements of comparable boundary conditions and applied forces

RESULTS

Pelvic Belts Alter SIJ Motion

The double-leg stance simulation without pelvic belt application provided a basic idea of the three-dimensional SIJ motion (Fig. 3). A rotation of the sacrum and the ilium around the transverse axis was observed. Additionally, the coxal bones rotated around a sagittal axis. The latter rotation can be described as an inward tilt of both iliac bones. When simulating pelvic belt application, the initial SIJ motion was altered as shown in Fig. 3.

Pelvic Belts Relieve Most Strained SIJ Ligaments

The effect of the pelvic belt was also reflected in the ligaments and the respective strain levels. The anterior, interosseous, posterior, and long posterior sacroiliac ligaments and the iliolumbar ligaments showed alignment- and region-dependent strain behavior. There-

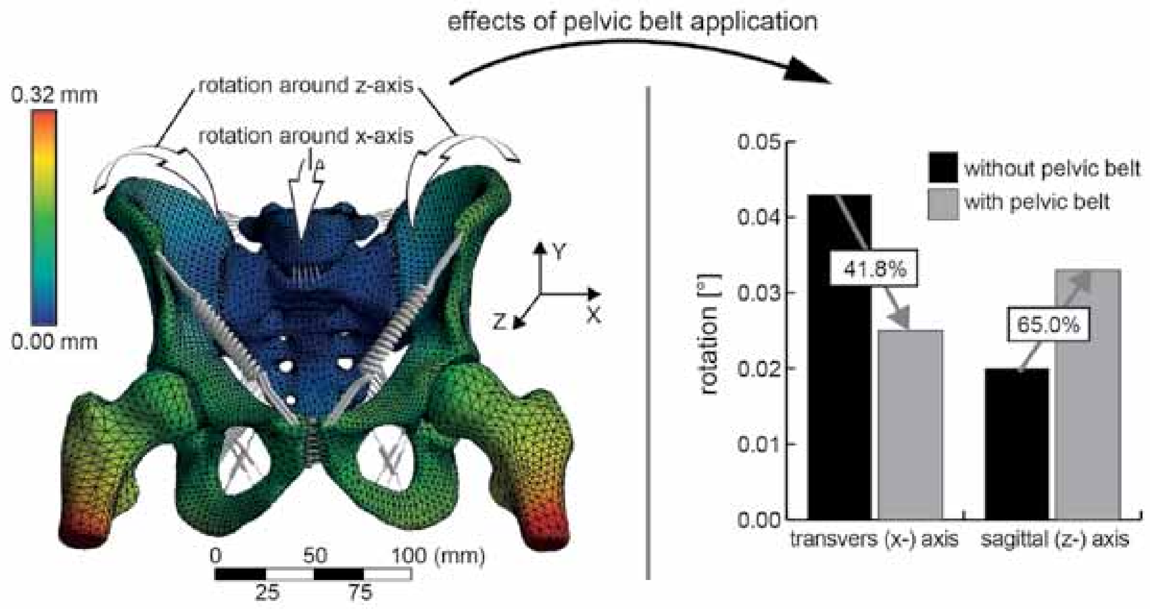

Fig. 3. *The computer simulation reveals how the coxal bones and the sacroiliac joint ligaments were deformed by the pelvic belt. The total deformation is shown in the double-leg stance scenario. Sacroiliac joint motion was detected in the sagittal z-axis and the transverse x-axis and is altered by the pelvic belt application. Due to its use, joint rotation in the transverse axis decreased and rotation in the sagittal axis increased. The total amount of rotation appeared minute but changed to a marked relative extent.*

fore, it was impossible to quote averaged ligament strains at this point. Instead, a quantitative description of the ligament strain behavior was given (strain levels were quoted in parentheses). For instance, the strain behavior of the interosseous ligaments (15 springs in our model) can be described as follows: Without pelvic belt application, 6 springs were strained (> 0.00 to 0.12%) and 9 springs were slackened (-0.14 to -0.02%). When the pelvic belt was applied, 3 springs remained strained (> 0.00 to 0.09%), 3 springs changed from a positive to a negative strain level (-0.14 to -0.06%), one spring changed from a slackened to a strained state (> 0.00%), and 8 springs remained slackened (-0.37 to -0.05%). In all of the strained interosseous ligaments, the strain levels decreased. The results for the anterior, posterior, and long posterior sacroiliac ligaments and the iliolumbar ligaments are summarized in Table 1. The sacrospinous and the sacrotuberous ligaments were strained homogeneously. During pelvic belt application, mean strain values for sacrospinous and sacrotuberous ligaments decreased from 0.072% to 0.059% and from 0.048% to 0.041%, respectively, compared to the scenario without pelvic belt application.

Computer Simulation Shows Good Agreement with Literature

For the initial double-leg stance scenario, the displacements in our computer simulation agreed with the results from literature. Both our predictions and the experimental data from Varga et al (46) indicate minute displacements within the pelvic ring. SIJ motion and resultant pelvic ligament strains predicted by Buford and coworkers (29) were also consistent with our results. A summary of the validation data is shown in Table 3.

DISCUSSION

This is the first study to quantify the influence of a pelvic belt on SIJ motion and the region-dependent effects on ligament loads. Our results support the hypothesis that pelvic belts alter SIJ motion to the effect that the most loaded ligaments are relieved. In particular, the pelvic belt caused a decrease in SIJ rotation around the transverse axis and an increase around the sagittal axis. These findings are in accordance with in-vitro effects of pelvic belts, as shown by Vleeming et al (47). The reduced rotation around the transverse axis can be attributed to an additional lateral compression on the

Table 3. Validation of the computer model using data from Buford et al (29) and Varga et al (46). We compared mean displacements between defined anatomical landmarks and resulting ligament strain for motion around the transversal axis. Underlying boundary conditions and applied loads were similar to our settings.

Literature	Validation Data	Predicted Results	Actual Results
Varga et al (46)	Mean displacement of the sacrum relative to the innominate bone	0.023 mm	0.003 mm
Varga et al (46)	Mean displacement of pubic symphysis in the plane of its anterior surface and in a horizontal line 1 cm below the inferior part of the symphyseal joint	0.022 mm	0.001 mm
Buford et al (29)	Mean strain of sacrotuberous ligament for motion around transversal axis of 0.043°	0.05%	0.08%
Buford et al (29)	Mean strain of sacrospinous ligament for motion around transversal axis of 0.043°	0.07%	0.04%

articular surfaces of the SIJ in the sense of force closure (36,48,49). In contrast, the increased inward tilt of the iliac bones in the frontal plane may be an effect of the lever arm of the pelvic belt. In our study, force application via the pelvic belt was localized mainly cranial to the articular surface and therefore above the center of rotation within the SIJ (50,51). Consequently, ligaments below the center of rotation tend to be further elongated, such as the caudal parts of the anterior and posterior sacroiliac ligaments. However, most of the ligaments were affected by the reduced SIJ motion around the transverse axis. The sacrospinous and sacrotuberous ligaments were relieved uniformly when a pelvic belt was applied. These results indirectly corroborate earlier findings that rotation around the transverse axis winds up and tenses the sacrospinous and sacrotuberous ligaments (12,45,52). Additionally, most interosseous, posterior, and long posterior sacroiliac ligaments, as well as the iliolumbar ligaments, were relieved. However, their strain values were non-uniform. These results appear to be realistic in the context of reports on various fiber directions of the interosseous and posterior sacroiliac ligament and the iliolumbar ligaments (17,38,40,51,53,54), and their function as multidirectional stabilizers (55). Concerning the sacrotuberous ligaments, our results are indicative with findings of Pel et al (37) who also determined an unloading of the sacrotuberous ligaments by coxal compression in a computational model. Yet, the results of Pel et al are hard to compare in general since their study only used one element to represent each of the ligaments and did not include the anterior and interosseous ligaments. A more advanced investigation of ligament load is provided by Eichenseer and coworkers (56). Their results show that during flexion, the most strained ligaments are the interosseous (about 3.5%), sacrospinous (about 3.5%), and sacrotuberous (about 2.0%) ligaments, supporting theories of the ligaments' stabilizing function during SIJ flexion. The stated average ligament strains, however, do not coincide with our results, which are much smaller (0.01% to 0.3%). This may be attributed to different material properties, model accuracy, or to the different boundary conditions (57).

Also, the extent of SIJ motion differed markedly between our study and the data of others (26-28,58). As an example, the maximum SIJ rotation around the transverse axis found in our configuration was 0.05°, while it was up to 2.3° in the studies of Sturesson et al (27,28,58). This may be related to the fact that there is an inconsistency in the existing techniques for analyses of in vivo, in vitro, and computer-simulated SIJ motions. Thus, future studies are needed to assess reliable SIJ motion tracking during double-leg stance. However, our minute range of SIJ motion and resultant small strain levels are supported by previous in vitro and computational studies (46,59,60). Also, the relative effect of the pelvic belt can be stated as a marked alteration of SIJ rotation around the transverse and the sagittal axis with -41.8% and +65.0%, respectively.

These results support the findings of others that the ligaments are involved in sensory-motor control (48) and associated painful conditions of the SIJ (21,22,48). As mechanoreceptors are capable of detecting minute deformation changes, pelvic belt-altered SIJ motion changes might be experienced as substantial (48). As described elsewhere (61), tension of the interosseous, sacrospinous, and sacrotuberous ligaments increase muscle activation patterns, resulting in stiffening and compression of the SIJ in the sense of force closure. These findings indicate that in addition to being the region of potential pain generators, the SIJ ligaments may also be integrated in neuromuscular feedback loops. Relieved ligament strain levels result in a decrease or change of muscle activation (22,36,62). Previous studies found that muscle imbalance patterns of the hip muscles may cause low back pain (63). These theories on interaction between ligaments and muscles grouped around the SIJ likely explain how pelvic belts contribute to reduced low back pain, as reviewed comprehensively elsewhere (12,21,64). This theory, however, requires more study to prove the quantitative involvement of ligaments in sensory-motor control.

The given data on the effects of pelvic belts on the ligaments have several limitations. It is a simplification of the complex reality to assign homogenous and linear material properties to examine the behavior of bones, cartilage, and ligaments. The same is true for the chosen boundary conditions, even if they were selected carefully to conform to natural SIJ motion. Furthermore, the model is limited by the exclusion of muscle forces from the osteoligamentous model, and the use of iliotibial tract material properties to characterize the ligament strain behavior. In total, this computational approach can be regarded as an abstraction of the pelvis. This approach, however, can help to understand the complexity of ligament biomechanics. To enhance the validity of our results, we suggest performing further validation and sensitivity studies of the computer model with patients or body donors. Additionally, reliable mechanical data for the ligaments are needed. Despite the relatively large number of spring elements used for the ligaments, even larger numbers of spring elements are required to deepen our understanding of the interaction of the ligaments on SIJ motion.

Virtual analyses of pelvic belt effects on the SIJ reveal that pelvic belts alter joint motion and cause partial relief of ligament strain. SIJ motion and ligament strain are altered to a minimal absolute amount, but relatively the effect is large. These findings indicate that beside the ligaments' function as passive stabilizers, they may also be involved in active feedback mechanisms as sensitive regulators of joint position. Consequently, pelvic belts would likely be of therapeutic effect in patients with pain originating from the SIJ.

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Conflict of interest

Each author certifies that he or she, or a member of his or her immediate family, has no commercial association (i.e., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted manuscript.

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