

REVIEW

A Systematic Review of the Morphology and Function of the Sacrotuberous Ligament

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The sacrotuberous ligament (STL) has been linked to conditions such as pelvic girdle pain and pudendal nerve entrapment, yet its contribution to pelvic stability is debated. The purpose of this review was to explore the current understanding of the STL and highlight any gaps in knowledge regarding its anatomy and function. A systematic search of the literature was conducted, focussing on the morphology and attachments of the STL, the relationship of the STL with surrounding structures, and its neurovascular supply and function. A total of 67 papers and four textbooks were obtained. The attachment sites of the STL are largely consistent; however, the extent of its connections with the long head of biceps femoris, gluteus maximus, piriformis, the posterior layer of the thoracolumbar fascia, and sacrospinous ligament are unclear. Morphometric parameters, such as mean STL length (6.4–9.4 cm), depth (0.3–0.4 cm), and width (1.8–3.5 cm, at its mid-point) are variable within and between studies, and little is known about potential side-, age-, or sex-related differences. The STL is pierced in several sites by the inferior and superior gluteal arteries, but information on its innervation pattern is sparse. Functionally, the STL may limit sacral nutation but it appears to have a limited contribution to pelvic stability. Some morphological aspects of the STL warrant further investigation, particularly its connections with surrounding structures, innervation pattern and function. Knowledge of the detailed anatomy and function of this ligament is important to better understanding its role in clinical conditions. *Clin. Anat.* 32:396–407, 2019. © 2018 Wiley Periodicals, Inc.

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INTRODUCTION

The sacrotuberous ligament (STL), positioned posteriorly and inferiorly in the pelvis, is associated morphologically and functionally with the sacroiliac joint. It is thought to provide a neurophysiological link between the vertebral column, pelvis, and lower limbs (Alderink 1991; Varga et al. 2008; Vleeming et al. 1989a; Vleeming et al. 1989b). From a phylogenetic perspective, the STL may represent the upper, degenerated vestige of the proximal BFlh tendon (Martin 1968), the main portion of which inserts into the lateral part of the medial facet of the ischial tuberosity (Battermann et al. 2011; Philippon et al. 2015; Siegelbauer 1930; Woodley and Mercer 2005). The

STL spans between the sacrum and the ischial tuberosity, forms the boundaries of the greater and lesser sciatic notches (together with the sacrospinous ligament [SSL]), and is closely related to surrounding muscles including gluteus maximus, piriformis, and the long head of biceps femoris (BFlh) (Standing 2016). Due to its numerous connections with

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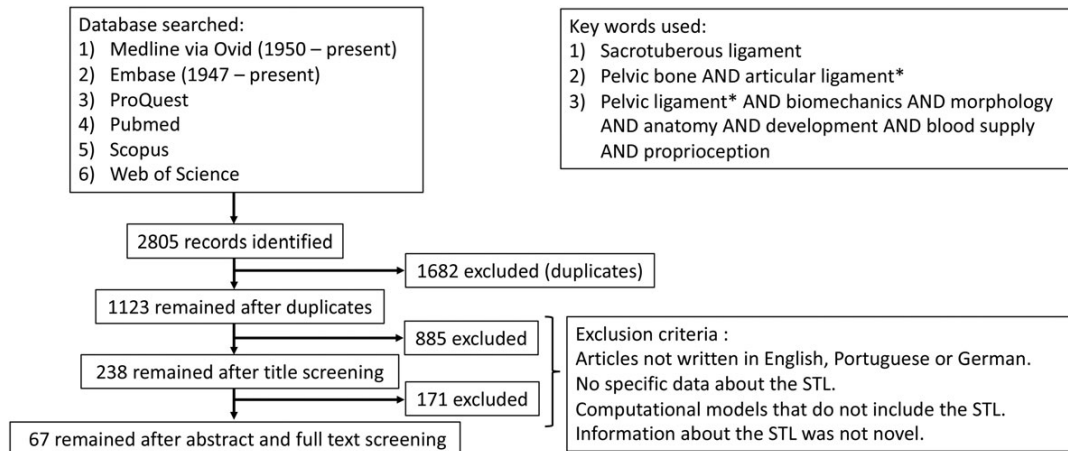


Fig. 1. Search strategy for the primary peer reviewed articles included in the review.

surrounding bony and soft tissue structures, the STL potentially has a complex role in the pelvic girdle.

Functionally, the STL is reported to assist in pelvic stability by acting passively to restrain excessive sacral nutation (anterior tilt of the sacral base) and more dynamically through its connections with lower limb and trunk muscles (van Wingerden et al. 1993; Vleeming et al. 1989a; Vleeming et al. 1989b). In the pelvic load transfer system model, the STL is considered to contribute to the posterior sling, connecting the perineum and biceps femoris muscle to the deep lamina of the thoracolumbar fascia and the erector spinae (Snijders et al. 1993a, 1993b). More recent findings suggest that the STL might also improve pelvic stability by providing proprioceptive information regarding pelvic position (Varga et al. 2008).

Although the STL has been linked to clinical conditions such as pelvic girdle pain and pudendal nerve entrapment syndrome, its exact role is debated. Patients with pelvic girdle pain might present with issues in the load transfer system of the pelvis as a result of altered force transmission of specific muscles connected to the STL, such as biceps femoris and gluteus maximus (Hungerford et al. 2003; Van Wingerden et al. 2004; Van Wingerden et al. 2008; Vleeming et al. 1989a). However, evidence for the STL contribution to pelvic girdle pain is unclear due to small sample sizes of the available studies (Hungerford et al. 2003), contrasting results (Bussey 2016; Hungerford et al. 2003), and uncertainty about the validity of methodological techniques (de Groot et al. 2004). In patients presenting with pudendal nerve entrapment syndrome, symptoms are believed to arise as a result of nerve compression at two main sites: between the STL and SSL, and/or at the pudendal canal due to compression by the falciform process, an extension of the STL reaching anteriorly along the ischium (Hough et al. 2003). Despite its close anatomical relationship to the pudendal nerve, the involvement of the STL in the aetiology of this nerve compression needs further investigation.

Understanding the detailed morphology, biomechanics, and function of the STL could potentially aid in elucidating its role in conditions such as pelvic girdle pain and pudendal nerve syndrome. In addition, due to its mechanical and neurophysiological complexity, its relevance to pelvic stability and control is not fully understood. Hence, the purpose of this review is to describe the morphological, biomechanical, and functional aspects of the STL.

METHODS

A systematic search of the literature was conducted to ensure all relevant studies on the STL were identified. Papers were identified by an electronic search conducted in six databases as well as a hand search of reference lists of relevant articles. The date of the last search was November 2018. Figure 1 presents the key words, databases searched and search strategy, and the number of studies identified.

Primary articles were considered as those that presented morphological, histological, or biomechanical data. Secondary articles contained relevant information about clinical aspects of the STL without direct assessment of its structure. Such information could be found in clinical hypothesis papers or papers with experimental designs that referred to the STL in the discussion session.

RESULTS

Overall, 67 studies presented morphological, histological, and biomechanical data related to the STL. Specifically, four studies described morphological aspects of the STL, 20 depicted its attachment sites and connections with surrounding structures, and 10 provided details regarding blood supply and innervation. Additionally, nine studies investigated the biomechanical aspects of the ligament and 24 computational model

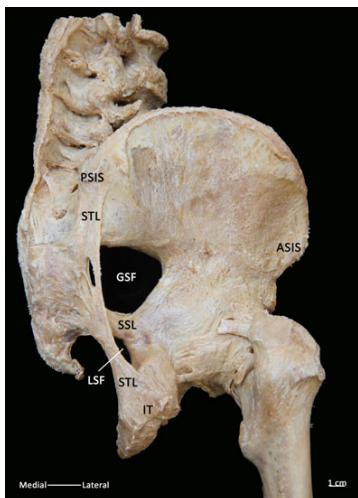


Fig. 2. Posterior view of a right hemipelvis showing the bony attachment sites of the sacrotuberous ligament (STL). ASIS, anterior superior iliac spine; GSF, greater sciatic foramen; IT, ischial tuberosity; LSF, lesser sciatic foramen; PSIS, posterior superior iliac spine; SSL, sacrospinous ligament. [Color figure can be viewed at wileyonlinelibrary.com]

studies considered the STL. Data from four contemporary and historical anatomical textbooks were included.

Attachment Sites

The attachments of the STL are diverse and, in some instances, descriptions are conflicting. Proximally, the broad base of the STL attaches to the posterior superior iliac spine, the long posterior sacroiliac ligament (with which it partially blends), and lower transverse sacral ligaments. It then descends to the inferior sacral tubercles and lateral margins of the inferior aspect of the sacrum and the superior aspect of the coccyx (Loukas et al. 2006; Standing 2016) (Fig. 2). A different description of the superior insertion of the STL is specifically the posterior border of the ilium between the posterior superior and posterior inferior iliac spines (Soames and Palastanga 2019).

Proximally, the relationship between the STL and the long posterior sacroiliac ligament is uncertain. The STL is described as an inferior extension of the posterior sacroiliac ligaments (Moore et al. 2010) or to attach to the long posterior sacroiliac ligament (Loukas et al. 2006; Moore et al. 2010; Standing 2016). Vleeming et al. (2007) proposed that the extended fibers of the STL that travel inferiorly from the long posterior sacroiliac ligament to the iliac bone should be named the tuberoiliac ligament (Vleeming et al. 2007). However, this connection has not been confirmed in histological observations of the long posterior sacroiliac ligament and its surrounding structures (McGrath et al. 2009).

From their proximal insertion sites the diagonal fibers of the STL run inferiorly and laterally, converging to form a narrow band that expands again to insert into the medial margin of the ischial tuberosity (Soames and Palastanga 2019; Standing 2016), with some connection to the BFLh (see "Relationship to surrounding structures"). Specific attachments of two distinct parts of the STL have also been described by Hammer et al. (2009). The superior fibers of the sacral portion of this ligament run dorsally and attach inferiorly to the ischial tuberosity, whereas the inferior portion runs ventrally to attach to the superior part of the ischial tuberosity.

Some of the STL fibers extend to the medial surface of the ischial tuberosity forming the membranous falciform process that lies just deep to the pudendal canal. Findings from Loukas et al. (2006) show that the falciform process has two different proximal attachment sites—the obturator fascia (69%) and an expansion to the ischioanal fossa (18%), which serves to link the STL, the obturator fascia, and the anococcygeal ligament through its medial aspect.

A detailed description of the STL attachment sites and variations reported in anatomical text books has been described in the past (Woodley et al. 2005). Since then, little information on the attachments of the STL has been added and some questions still remain. For example, the exact attachment sites of STL on the coccygeal, sacral, and iliac bones are unclear, and it is uncertain whether there are sex-related variations in anatomical parameters such as attachment sites and fiber orientation.

Morphometry

It is generally accepted that the STL forms a triangular, twisted shape and is present bilaterally in humans (Soames and Palastanga 2019; Seizeur et al. 2005). More recently, this two-dimensional description has been furthered via three-dimensional modeling with the ligament portrayed as presenting as a contorted bifurcated structure (two cones with three elliptical planes: origin, middle, and insertion) (Hammer et al. 2009). The twisted aspect of the ligament is likely to be the result of tensile forces exerted on the pelvis (Hammer et al. 2009) and means the ligament is larger at its ends than in its middle portion (Soames and Palastanga 2019).

Six studies have explored the morphometric characteristics of the STL, primarily focusing on its length, depth, and width (Table 1). The mean length of the STL is variable ranging from 6.4 to 9.4 cm (Hammer et al. 2009; Lai et al. 2017; Seizeur et al. 2005), although its mean depth (at the middle section of the ligament) is more consistent at 0.3–0.4 cm (Hammer et al. 2009; Loukas et al. 2006). The mean width of the STL has been assessed at three different locations, including its origin (4.9–7.6 cm), mid-point (1.8–3.5 cm), and distal insertion (2.3–5.8 cm). Differences in methods and approaches used for measuring the STL are likely to explain the wide range of available morphological data. For example, Seizeur et al. (2005)

TABLE 1. Morphometric Parameters of the Sacrotuberous Ligament (STL) as Described in the Literature

Study	Number (sex) of specimens	Outcome measure	Dimensions Mean (range)	Main findings
Seizeur et al. (2005)	8 (5M, 3F)	Superolateral Length • Right • Left Inferolateral Length • Right • Left Surface area • Right • Left	8.7 (7.1–9.7) 9.4 (8.4–10.4) 6.7 (4.2–7.5) 6.6 (5.4–7.9) 180 (120–266) 185 (130–256)	No significant morphometric differences between sides
Loukas et al. (2006)	50 (35M, 15F)	Length Width • Origin ¹ • Middle • Insertion ¹ Depth ² • Middle Width ³ • Origin • Middle • Insertion Depth ⁴ • Origin • Middle • Insertion Length Cross-sectional area • Origin • Middle • Insertion Perimeter • Origin • Middle • Insertion Surface ⁵ Volume	8.6 (6.5–12.1) 7.6 (5.2–9.2) 3.5 (2.2–4.5) 5.8 (4.2–7.5) 0.4 (0.2–0.5) M: 4.9 (1.8–7.9) F: 5.0 (2.0–7.5) M: 1.9 (1.0–3.9) F: 1.8 (0.7–3.4) M: 2.4 (1.6–4.3) F: 2.3 (0.2–4.6) M: 0.3 (0.1–0.7) F: 0.3 (0.1–0.8) M: 0.3 (0.1–0.7) F: 0.3 (0.1–0.6) M: 0.4 (0.2–0.8) F: 0.3 (0.1–0.7) M: 6.4 (4.5–8.5) F: 7.0 (4.6–9.0) M: 12.2 (2.8–32.4) F: 11.6 (1.6–35.3) M: 4.6 (1.4–12.1) F: 4.0 (0.7–14.1) M: 6.6 (2.8–13.8) F: 5.5 (0.8–10.7) M: 9.9 (3.8–15.8) F: 10.2 (4.1–15.2) M: 4.1 (2.2–7.8) F: 3.8 (1.5–6.8) M: 5.0 (3.4–8.8) F: 4.7 (1.0–8.0) M: 396.4 (154.0–624.5) F: 427.0 (229.6–701.0) M: 429.7 (202.8–968.1) F: 418.6 (143.6–898.5)	No morphometric differences with respect to race, age or gender STL was classified into 3 groups according to the morphology of the falciform process
Hammer et al. (2009)	50 (24M, 35F)	Length Cross-sectional area • Origin • Middle • Insertion Perimeter • Origin • Middle • Insertion Surface ⁵ Volume	M: 6.4 (4.5–8.5) F: 7.0 (4.6–9.0) M: 12.2 (2.8–32.4) F: 11.6 (1.6–35.3) M: 4.6 (1.4–12.1) F: 4.0 (0.7–14.1) M: 6.6 (2.8–13.8) F: 5.5 (0.8–10.7) M: 9.9 (3.8–15.8) F: 10.2 (4.1–15.2) M: 4.1 (2.2–7.8) F: 3.8 (1.5–6.8) M: 5.0 (3.4–8.8) F: 4.7 (1.0–8.0) M: 396.4 (154.0–624.5) F: 427.0 (229.6–701.0) M: 429.7 (202.8–968.1) F: 418.6 (143.6–898.5)	No differences between sides Women had a significantly greater height at origin and length, but significantly smaller cross-sectional area
Lai et al. (2017)	21 hemipelvises, 8 left and 13 right (equal number of M and F)	Width • Origin Length	6.3 (5.0–8.0) 6.8 (5.5–8.1)	

To allow comparison between studies some of the variables' names were changed. The lengths, depths, perimeter and widths are presented in cm, the surface and cross-sectional areas are presented in cm², and the volumes in cm³. Abbreviations: F, female; M, male

¹ Origin and insertion were described in the original paper as proximal and middle.

² Depth was described as thickness.

³ Width was described in the original paper as height.

⁴ Depth was described as width.

⁵ Surface was described as the lateral surface in the original paper.

obtained two measurements of STL length, from both its superolateral and inferolateral margins, relative to the ischial tuberosity. In contrast, Lai et al. (2017) considered the STL as a single distance between the middle width of its sacral portion and the ischial tuberosity.

Other measures such as surface, perimeter, and cross-sectional area are also important considerations. Surface area is described in two studies with a substantial difference in mean values, ranging from 185.0 to 427.0 cm² (Hammer et al. 2009; Seizeur et al. 2005).

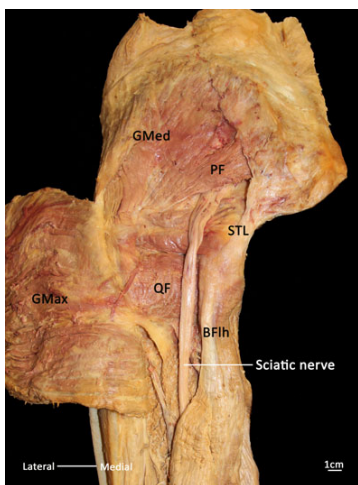


Fig. 3. Posterior view of the left hemipelvis and thigh showing the connection between the sacrotuberous ligament (STL) and proximal tendon of the long head of the biceps femoris (BFLh) muscle. GMax, gluteus maximus; GMed, gluteus medius; PF, piriformis; QF, quadratus femoris. [Color figure can be viewed at wileyonlinelibrary.com]

Currently, there is no evidence to suggest that the morphology of the STL differs based on side or race (Hammer et al. 2009; Seizeur et al. 2005); however, findings relating to age and sex differences are conflicting (Hammer et al. 2009; Loukas et al. 2006). For instance, the STL has been reported to have a significantly larger cross-sectional area at its origin (sacral insertion) in older cadavers; however, the parameters were weakly correlated ($r = 0.23$) (Hammer et al. 2009). Hammer et al., (2009) also reported that STL width (referred to as height in their paper) and length were greater in women, whereas cross-sectional area was larger in men. Sex differences were “not noticed” by Loukas et al., (2006) although no descriptive or inferential analyses were presented to support this observation. It is probable that if they exist, sex-related differences in STL morphometrics are linked to sex-specific pelvic outlet dimensions. As shown by Seizeur et al., (2005), certain pelvic outlet dimensions such as sacral angle and slope correlate with some STL dimensions. However, it is important to note that the studies which compared groups have not normalized their data, for example by height or weight.

Falciform process The falciform process is a membranous, non-ligamentous portion of the STL, and this morphological feature is considered to contribute to the aetiology of pudendal nerve entrapment (see “Relationship to surrounding structures”) (Robert et al. 1998). However, morphometric data on this structure are limited to one study. Loukas et al. (2006) reported that 87% of 50 cadaveric specimens had a falciform process (one specimen presented with unilateral occurrence of the falciform process) and observed two main variations with respect to its ischial

ramus attachment site. Falciform ligaments attaching to the obturator fascia (69% of cases) had a mean length of 1.6 cm (range 1.2–2.0 cm), whereas those with expanded attachment sites to the ischial fossa were on average three times longer (mean length 4.6 cm, range 3.5–5.4 cm). The latter type of falciform process was firmly adhered to the pudendal nerve and considerably narrowed the space lateral to the nerve.

Relationship to Surrounding Structures

The STL has complex topographical and functional interactions with its surrounding structures. It has been observed that this ligament has connections with gluteus maximus, piriformis, and the BFLh and also to the superficial dorsal fascia. Furthermore, the ligament shares a common attachment site at the sacrum with the SSL.

Biceps femoris Functionally, the connection between the STL and proximal tendon of BFLh (Fig. 3) is thought to be important in the transfer of forces across the SIJ (van Wingerden et al. 1993; Vleeming et al. 1989a). However, the morphological relationship between the STL and BFLh is not well defined, with only five dissection studies reporting on this connection. Two studies (Martin 1968; Philippon et al. 2015) acknowledge that a portion of the STL is confluent with the proximal BFLh or conjoined semitendinosus-BFLh tendon but do not provide further details. While it is intuitive that the superficial, posterior fibers of the BFLh tendon (Sato et al. 2012; van Wingerden et al. 1993) are those more likely to interact with the ligament, there are no data regarding the exact proportion of tendinous fibers that do contribute to this tendon-ligament complex. Current evidence suggests that variation exists in the continuity between the STL and BFLh tendon. van Wingerden et al. (1993), in a study of 10 specimens, reported specifically that the lateral superficial fibers of the STL blend with the BFLh tendon. However, this connection was inconstant, being evident in 60% of cases, with the STL inserting solely into the ischial tuberosity in the remaining 40%. This variable attachment site was also described by Vleeming et al. (1989b), in a group of 23 cadavers (46 specimens), whereby fusion between the STL and BFLh was observed in 48% (11/23) of individuals and 38% (17/46) of specimens. The disparity in percentages is due to six individuals (five of whom were female) having bilateral connections and unilateral STL-BFLh connections in the remaining five individuals. More recently, Sato et al. (2012) undertook a dissection and histology study in 28 specimens from 14 cadavers to examine the proximal hamstring insertions. Their dissection findings were in contrast to those of van Wingerden et al. (1993) and Vleeming et al. (1989b), whereby it was observed that the posterior portion of the BFLh (but not the proximal semitendinosus tendon) was “widely connected” to the STL in all 20 specimens. Interestingly, in 3/20 (15%) the majority of STL fibers appeared to exclusively blend with the BFLh tendon, with no attachment to the ischial tuberosity. The

seemingly robust connection of the ligament-tendon complex was confirmed histologically, with no separation of the tissues noted; rather the STL and BFlh tendon were reported to be at least partially connected to each other. Further investigation is required to confirm the extent of the connection between these two structures.

Gluteus maximus The STL is said to fuse with the lower fibers of gluteus maximus posteriorly. However, no data are available that report the extent of these fusions/attachments, or how commonly these attachments are observed (Standring 2016; Vleeming et al. 1989a). Barker et al. (2014) state that all 11 specimens (6 cadavers; 2 females, 4 males; age 54–90 years) dissected in their study that focused on the biomechanics of gluteus maximus, showed a muscular attachment of gluteus maximus onto the posterior surface of the STL. Although the dimensions of the connection between these structures were not quantified, the PCSA of this connection was estimated to be 4.2 (range 1–9) cm². The mean estimated force capacity of this interaction is equivalent to 207 N, contributing to 23.5% of the compression forces that gluteus maximus generates across the SIJ.

Piriformis Similar to gluteus maximus, the upper part of the pelvic surface of the STL may be a site of attachment for piriformis (Standring 2016), but no data explain the nature of this insertion (Vleeming et al. 1989a). Ravindranath et al. (2008) refer to an accessory muscle of piriformis being present in three cadavers (male, adult), with the fibers of this muscle attaching to the STL in all three cases, as well as the fascia overlying gluteus medius in one. The extent of the attachment is not described or measured, and the accompanying photographs are difficult to decipher. However, the accessory muscle itself measured 2–3 cm in width, indicating a small connection compared to the overall size of the ligament.

Another case study of a male cadaver (63 years) showed a variation in the piriformis muscle, which presented as two bellies. Only the inferior belly (pictured as the smaller of the two bellies) originated from the STL by “a single digitation” (Arifoglu et al. 1997) implying a small muscular interaction with the ligament. In a review paper, Smoll (2010) report an attachment between piriformis and the STL, but provide no data, nor reference from which this information is derived.

Posterior layer of the thoracolumbar fascia Two dissection studies provide data on the relationship between the STL and thoracolumbar fascia. One study that examined the layers of the thoracolumbar fascia in 40 embalmed cadavers (22 female, 18 male; age 59–84 years) indicates a possible connection between the STL and the posterior layer of the thoracolumbar fascia (Loukas et al. 2008), but it is not clear whether the fascia attaches to the ligament or is located nearby. In 10 embalmed cadavers (6 male, 4 female; 65–90 years), Vleeming et al. (1995) dissected the

layers of the thoracolumbar fascia and noted its connections to the STL; the fibers of the deep layer of the fascia are continuous with the ligament.

Sacrospinous ligament The STL and the SSL have a close connection, in particular at their combined attachment site at the lateral sacrum (Vleeming et al. 2002) (Fig. 4). The SSL lies deep and anterior to the STL, and the superior fibers on the medial aspect of the SSL blend with the STL at the sacral level (Standring 2016). More specifically, these ligaments are physically connected at a median distance of 1.6 cm (range 0.6–3.6 cm) from the ischial spine (Florian-Rodriguez et al. 2016).

Functionally, it has been suggested that both ligaments limit sacral movement on the iliac bones, resisting nutation of the sacrum (Slocumb and Terry 1926; Vleeming et al. 2007). Recently Hammer et al. (2009) have challenged this idea, hypothesizing that the SSL and STL may have opposite functions. Due to its twisted morphology, tensioning the STL is likely to lift the ischium in relation to the sacrum, whereas tension to the SSL lowers the ischium. Despite their contrary roles, the STL and SSL are moderately correlated with respect to their volume and cross-sectional area at their origins ($P < 0.001$, $r = 0.58$ for volume and 0.55 for cross-sectional area) (Hammer et al. 2009). In addition to their role at the SIJ, the STL and SSL contribute to the boundaries of the greater and lesser sciatic foramina (Roshanravan et al. 2007).

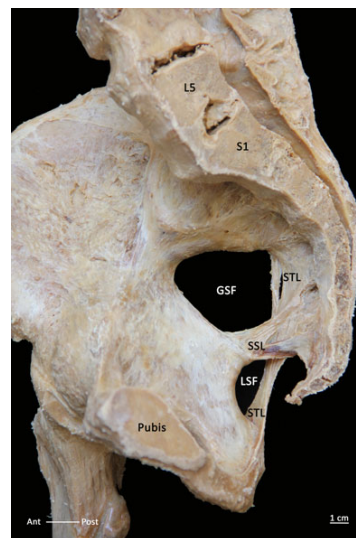


Fig. 4. Medial view of a right hemipelvis demonstrating the relationship between the sacrotuberous (STL) and sacrospinous (SSL) ligaments. Ant, anterior; GSF, greater sciatic foramen; LSF, lesser sciatic foramen; Post, posterior. [Color figure can be viewed at wileyonlinelibrary.com]

Pudendal nerve There is no confirmation that the pudendal nerve and artery have a functional connection with the STL. However, numerous clinical studies have highlighted the relationship between these structures and suggest that the STL is a cause of pudendal nerve entrapment syndrome. According to Robert et al. (1998), the pudendal nerve is potentially compressed at three sites: between the STL and SSL, in the pudendal canal, and around the falciform process. The pudendal nerve meets the STL at the level of the ischial spine, lying between the SSL (anteriorly) and the STL (posteriorly). The falciform process has an intimate relationship with the pudendal nerve, and according to Loukas et al. (2006), the morphometry and attachment sites of the falciform process determine the diameter of the pudendal canal.

Neurovascular Supply

In most cases, the vascular supply to the STL is reported as a secondary finding in anatomical investigations related to underlying mechanisms of pudendal nerve entrapment. However, three anatomical studies contribute specific information on the vascular aspects of the STL (Hammer et al. 2009; Loukas et al. 2006; Thompson et al. 1999) and one provides a detailed description (Lai et al. 2017). Two studies report that the coccygeal branch of the inferior gluteal artery penetrates the STL at numerous sites and exits the pelvis, as the coccygeal branch, through this ligament (Loukas et al. 2006; Thompson et al. 1999). More specifically, Loukas et al. (2006) describe the coccygeal branch as passing dorsally to the midpoint of the SSL, piercing the STL at several locations. In another study, the inferior gluteal artery was described to penetrate the STL close to its sacral attachment, forming two distinct patterns (Hammer et al. 2009). In 69% of cases, one artery pierced the STL, whereas two arteries penetrated it in 8% of cases. No differences were found between sex or side of the body.

In a recent study by Lai et al. (2017), the arterial supply of the STL was described based on findings from 21 hemipelvises (16 cadavers, 8 males). They report that the STL is not exclusively supplied by the inferior gluteal artery as previously described. Rather, both the inferior and the superior gluteal artery (coccygeal branches) cross the STL, in several locations close to the ischial tuberosity. The superior gluteal artery (sacral branches) pierces the STL near the sacrum supplying blood to the medial and proximal aspect of the STL, that is, the width of the ligament (Lai et al. 2017). Interestingly, the morphology of the STL does not seem to influence the number of sacral or coccygeal branches. For example, the length of the STL did not correlate with the number of coccygeal entrances and its width did not correlate with the number of sacral branches.

The innervation pattern of the STL is rarely documented (Florian-Rodriguez et al. 2016), with most studies only presenting its anatomical relationship with the pudendal nerve (Cvetanovich et al. 2018; Juenemann et al. 1988; Schraffordt et al. 2004). In one dissection study of 12 specimens, Robert et al.

(1998) reported a few occurrences (number not provided) of the pudendal nerve entering and traveling parallel with the fibers of the STL (Robert et al. 1998). Florian-Rodriguez et al., (2016) reported that 85% of 14 cadaveric specimens received between 1 and 3 branches from the S3 and/or S4 nerves—they either pierced or coursed through the STL. In these studies, however, information was exclusively about the anatomical relationship between these structures, with no confirmation of whether the pudendal nerve actually innervates the ligament.

A histological description of the nerve endings present in the STL has been reported in one study (Sato et al. 2012; Varga et al. 2008). Varga et al. (2008) examined the occurrence of nerve fibers in the STL and SSL, to explore whether these ligaments have a proprioceptive role in addition to their proposed mechanical function. This study revealed the existence of sensory nerve endings, classified as being similar to Ruffini-type receptors, in both ligaments. Nerve endings were more concentrated near the ischial tuberosity, particularly in the STL, but their densities were not quantified.

Function of the STL

The roles of the STL in restricting sacral movement and assisting with pelvic stabilization have been derived from both biomechanical studies and computational models.

Biomechanics Nine biomechanical studies related to the STL have assessed the role of this ligament on pelvic biomechanics in variable numbers of cadaveric specimens (Abdelfattah and Moed 2014; Conza et al. 2007; Shobeiri et al. 2000; Slocumb and Terry 1926; Varga et al. 2008; Vleeming et al. 1989b; Vleeming et al. 1996; Vrahas et al. 1995; Vukicević et al. 1991) (Table 2). In two studies, the STL was purported to limit pelvic motion. This observation was supported by findings that showed an increase in sacral nutation after sectioning the STL and SSL (Slocumb and Terry 1926) and increased tension of this ligament when sacral nutation was externally induced (Vleeming et al. 1989b). On the other hand, the contribution of the STL on pelvic kinematics appears to be minimal (Abdelfattah and Moed 2014; Conza et al. 2007; Varga et al. 2008; Vrahas et al. 1995; Vukicević et al. 1991). For instance, some studies have explored the effect of load on pelvic kinematics, with a fixed load applied to the lumbar spine or sacrum prior to, and after, the removal of the STL. Findings suggest no changes in pelvic deformation (Vukicević et al. 1991), pelvic stiffness (Vrahas et al. 1995), vibrometry (Conza et al. 2007), and pubic symphysis or sacroiliac joint dislocation (Varga et al. 2008) between pre-STL and post-STL removal. In addition, data regarding the mechanical properties of the STL in isolation are conflicting with the mean point failure of this ligament occurring on average at 80 N (Varga et al. 2008) or 434.4 N (Shobeiri et al. 2000).

The limited influence of the STL on pelvic integrity might be related to experimental protocol restrictions. Under such experimental conditions, pelvises are

TABLE 2. Biomechanical Studies Related to the STL Described in the Literature

Authors	Number (sex) of specimens Age range	Methods	Outcome measures	Main findings ¹
Stocumb and Terry (1926)	30 (27M, 3F) cadaver pelvises 20–83 yr	Pelvises were fixed and a vertical fixed load (75 kg) applied to the lumbar spine toward the sacrum	Sacral excursion (mm) with the STL and SSL intact and severed	87% of the pelvises presented posterior movement of the lower part of the sacrum after severing ligaments Total excursion ranged from 0 to 2.5 mm
Vleeming et al. (1989b)	4 (1M, 3F) cadaver pelvises 73–83 yr	Pelvises were fixed and an external load generating counternutation (dorsal bilateral 200 N and caudal bilateral 100 N) or nutation (cranial bilateral 200 N and ventral bilateral 100 N) was applied; a laterocaudally fixed load (50 N) was applied to the STL	Sacral rotation as a result of STL loading during nutation and counternutation (100 N) was calculated based on sacral displacement measurements	Nutation plus STL load resulted in significant decrease of nutation Counternutation plus STL load resulted in significant increase in counternutation in 3/5 hemipelvises
Vukicevic et al. (1991)	12 (sex not described) fresh cadaver pelvises	Pelvises were fixed and a load (50–300 N) applied over the first lumbar vertebra	Holographic assessment of the pelvis with intact STL and/or SSL and after removal	Deformation patterns of the pelvis were not affected by the removal of STL and/or SSL
Vrahas et al. (1995)	20–40 yr 13 fresh cadavers comprised L4 and L5 vertebrae Age not described	Pelvises were fixed simulating a standing position and a vertical fixed load (600 N) applied to the L4 toward the sacrum	Load displacement curve as measured with intact pelvic ligaments and after cutting all pelvic ligaments Stiffness was calculated at loads between 100 N and 150 N	Mean stiffness with intact ligaments was 129 ± 54 N/mm ranging from 34 to 259 N/mm Cutting STL and SSL had little to no effect on pelvic stiffness (mean 3% drop in stiffness ranging from 0 to 8%). Limitations: STL and SSL were cut together
Vleeming et al. (1996)	6 cadaveric (1M, 5F) specimens 70–92 yr	A traction force of up to 50 N was applied unilaterally to the STL, biceps femoris, fascia, and superficial fibers of the gluteus maximus and posterior layer of the thoracolumbar fascia	The effect of traction to surrounding soft tissues on the long posterior sacroiliac ligament	Traction of the STL significantly increased the tension of the posterior sacroiliac ligament, and it was significantly greater compared with biceps femoris and gluteus maximus

(Continues)

TABLE 2. Continued

Authors	Number (sex) of specimens Age range	Methods	Outcome measures	Main findings [†]
Shobeiri et al. (2000)	17 (8 STL from F) fresh cadavers Older than 50 yr	Bone-ligament-bone complexes were aligned with the testing machine and a tensile force (50 mm/s) was applied until failure	Overall stiffness, maximum load, and displacement to failure of the STL, SSL, and polypropylene sutures were measured	Mean \pm SD of failure load and stiffness were 434.6 N \pm 174.7 N and 26.5 N/mm \pm 7.9 N/mm. Mean displacement of failure was 16 mm (no clear data about variability)
Varga et al. (2008)	8 (6M, 2F) cadaver pelvises 61–85 yr	Pelvises were fixed simulating a standing position and a vertical cyclical load (100 Hz maximum of 500 N) applied to the proximal sacrum	Mean pelvic ring stiffness and displacement of the pubic symphyses and the sacroiliac joints were measured in an intact pelvis and after severing the STL or SSL and both	Mean STL stiffness and load and displacement at failure were statistically greater than SSL Limitations: Cross-sectional area not measured. Tensile force was unidirectional Pubic symphyses and sacroiliac joint displacement, pelvic ring stiffness in pelvises with intact ligaments were similar to the pelvises with dissected ligaments
Conza et al. (2007)	1 fresh-frozen human pelvis Sex and age not described	Failure test was performed	Tensile strengths of the intact STL and SSL were measured	STL and SSL were able to resist up to 80 N (on average) before failure. Tensile strength of STL and SSL were similar
Abdelfattah and Moed (2014)	6 embalmed pelvic specimens Sex and age not described	Vibration testing using one dimensional laser vibrometry (10–340 Hz) A manual external rotation was applied to the left ilium with the right ilium being constrained. This was done after sectioning the pubic symphyses followed by sectioning the STL/SSL and later the ASIT (Group 1) or the ASIT and then the STL/SSL (Group 2)	Frequency responses (frequency, damping level and shape) with intact ligaments and after the STL and SSL resection Horizontal and vertical displacement relative to the unfixated pelvis was assessed in Group 1 and 2	Results were exclusively associated to the vibrations used Both horizontal and vertical displacement were not different between groups

Abbreviations: ASIT, anterior sacroiliac ligaments; SSL, sacrospinous ligament; STL, sacrotuberous ligament; yr, years.
[†] Main findings were restricted to the STL.

tested in a position that simulates bilateral standing with an external load applied over the sacrum or the lumbar vertebrae. A bilateral standing posture, *in vivo*, is sustained and controlled by postural muscles, including biceps femoris, gluteus maximus, and the posterior layer of the thoracolumbar fascia, which based on computational models and biomechanical testing also contribute to pelvic stability (Pel et al. 2008). As the STL is intimately connected to these muscles, its function will likely be influenced by their activity and not exclusively determined by its own mechanical properties. This hypothesis is partially demonstrated by Vleeming et al. (1989b) who loaded the STL from a latero-caudal direction, simulating the actions of the biceps femoris and the gluteus maximus muscles. It is suggested that this influenced the STL and resulted in an increase in SIJ compression forces (Vleeming et al. 1989b).

Computational models In the current literature, 24 computational models that incorporate the STL into their simulations are available. Of these, 23 studies utilized the finite elements method (Arkusz et al. 2018; Bodzay et al. 2014; Böhme et al. 2011; Böhme et al. 2014; Bruna-Rosso et al. 2016; Eichenseer et al. 2011; Fu et al. 2014; García et al. 2000; Hammer et al. 2013; Hao et al. 2011; Hu et al. 2017; Ivanov et al. 2009; Kiapour et al. 2012; Kim et al. 2014; Lei et al. 2015; Lindsey et al. 2015, 2018; Ma et al. 2015; Shi et al. 2014; Sichting et al. 2014; Sztrinkai et al. 2014; Zhang et al. 2014; Zhao et al. 2012), and one used a kinematic simulation approach (Buford et al. 2010). Seven of these studies performed basic science biomechanical analyses (Arkusz et al. 2018; Buford et al. 2010; Eichenseer et al. 2011; Hao et al. 2011; Hu et al. 2017; Shi et al. 2014), whereas pelvic injury and subsequent surgical treatment were the focus of 14 studies (Bodzay et al. 2014; Böhme et al. 2011; Böhme et al. 2014; Bruna-Rosso et al. 2016; Fu et al. 2014; García et al. 2000; Ivanov et al. 2009; Lei et al. 2015; Lindsey et al. 2015, 2018; Ma et al. 2015; Sztrinkai et al. 2014; Zhang et al. 2014; Zhao et al. 2012). In three studies, numerical experiments were undertaken on the diagnosis and nonsurgical treatment of pelvic pain (Kiapour et al. 2012; Kim et al. 2014; Sichting et al. 2014).

The extent to which anatomical and biomechanical detail of the STL has been included varies vastly between studies. Mostly linear elastic material properties were assigned and commonly as tension-only spring elements (Arkusz et al. 2018; Bodzay et al. 2014; Böhme et al. 2011; Böhme et al. 2014; Fu et al. 2014; García et al. 2000; Hao et al. 2011; Hu et al. 2017; Lei et al. 2015; Shi et al. 2014; Sichting et al. 2014; Sztrinkai et al. 2014; Zhao et al. 2012). The material properties assigned to the STL vary between 33.2 MPa (Böhme et al. 2011) and 397.0 MPa (Böhme et al. 2014; Hammer et al. 2013), or 0.042 N/mm (García et al. 2000) and 9,000 N/mm (Zhang et al. 2014) for elastic modulus and ligament stiffness, respectively. Highly accurate ligament fiber orientations based on extensive anatomical dissection and imaging can be derived from one study (Sichting et al. 2014), as most others only include gross fiber orientations

(Böhme et al. 2011; Böhme et al. 2014; Buford et al. 2010; Eichenseer et al. 2011; Hammer et al. 2013; Hu et al. 2017; Ivanov et al. 2009; Kiapour et al. 2012; Kim et al. 2014; Lindsey et al. 2015, 2018; Shi et al. 2014), with some using inaccurate ligament attachments for their modeling (Arkusz et al. 2018; Bodzay et al. 2014; Bruna-Rosso et al. 2016; Fu et al. 2014; García et al. 2000; Hao et al. 2011; Lei et al. 2015; Ma et al. 2015; Sztrinkai et al. 2014; Zhang et al. 2014; Zhao et al. 2012). Moreover, the dimensions of the ligament attachment sites vary vastly between 1.3 mm² (Arkusz et al. 2018) and 539.0 mm² (Lei et al. 2015), and this difference does not explain for variations in the material properties. Beyond the modeling issues, validation of the numerical simulations has been performed inconsistently and only 10/24 experiments compare to physical validation data (Bodzay et al. 2014; Böhme et al. 2011; Böhme et al. 2014; Bruna-Rosso et al. 2016; García et al. 2000; Hammer et al. 2013; Hao et al. 2011; Hu et al. 2017; Ivanov et al. 2009; Lei et al. 2015). Literature-based comparison appears to be the most common approach (Arkusz et al. 2018; Buford et al. 2010; Eichenseer et al. 2011; Fu et al. 2014; Kiapour et al. 2012; Kim et al. 2014; Lindsey et al. 2015, 2018; Ma et al. 2015; Shi et al. 2014; Sichting et al. 2014; Sztrinkai et al. 2014; Zhang et al. 2014; Zhao et al. 2012), with a number of studies omitting comparison to consistent loading scenarios.

Eight of the 24 computational modeling studies report on the involvement of the STL from their simulations, with varying hypotheses and outcomes. With respect to movement, it has been reported that the STL is strained under either extension (Buford et al. 2010), or flexion and axial rotation (Eichenseer et al. 2011) of the lumbosacral region. Increased STL stiffness causes reduced motion at the acetabulum and pubic symphysis, in line with other pelvic ligaments, but at the same time increases motion at the sacrum (Hammer et al. 2013). Specifically modeling the synovial part of the SIJ is related to increased strain at the STL (Shi et al. 2014). Other studies have a slightly more clinical slant and consider STL injury and assessment of the joints of the pelvic girdle. García et al. (2000) reported that injury to the STL increases pelvic displacement at both the SIJ and pubic symphysis, a finding which has since been confirmed for the SIJ (Ivanov et al. 2009). Kim et al. (2014) assessed the effects of six diagnostic tests for SIJ pain (Van der Wurff et al., 2000a; Van der Wurff et al., 2000b) using the model developed by Ivanov et al. (2009). They report that the STL does not undergo any significant stretching during any of these tests. In relation to the effect of pelvic orthoses, Sichting et al. (2014) conclude that their application decreases tension in the STL.

CONCLUSION

This review provides a contemporary perspective on the morphological and biomechanical characteristics of the STL. Most of the information regarding ligament attachment sites is consistent, however, uncertainty surrounds the exact dimensions of the STL and data are inconsistent for potential sex- and

age-related differences. Similarly, the relationship between the STL and surrounding structures, particularly the BFlh, gluteus maximus, and thoracolumbar fascia requires further clarification, specifically to quantify the extent and nature of these connections. Blood supply to the STL is via the superior and inferior gluteal vessels but its gross innervation pattern, together with the presence and distribution of nerve endings, has not been reported in detail. Furthermore, findings from biomechanical studies and computational models are conflicting about whether the STL has an important (or any) role in pelvic stability; it is possible that methodological limitations of such studies influenced the results regarding the function of the STL. Hence, a detailed understanding of the morphology of the STL is vital to inform future computational modeling studies and also to advance knowledge around the role of this ligament in clinical conditions such as pelvic girdle pain.

CONFLICT OF INTEREST

All the authors of this manuscript declare that the research was conducted in absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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