Annals of Anatomy 236 (2021) 151698

Contents lists available at ScienceDirect

Annals of Anatomy

journal homepage: www.elsevier.com/locate/aanat

RESEARCH ARTICLE

The topography and morphometrics of the pubic ligaments

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ARTICLE INFO

Article history:
Received 17 August 2020
Received in revised form 11 January 2021
Accepted 15 January 2021
Available online 11 February 2021

Keywords:
Pubic ligaments
Symphysis pubis
Groin pain
Pelvic anatomy

ABSTRACT

Background: Conflicting anatomical reports and the little attention given to the pubic ligaments impede the interpretation of radiological and clinical examinations on groin pain. Morphometric data on the pubic ligaments are lacking.
Methods: The muscular relations of the symphysis pubis were examined in layered dissection (n = 10), hemipelves (n = 60) and (un)stained plastinated body slices of body donors (n = 3). The sagittal and coronal areas, width, mean and maximum thickness of pubic ligaments were determined.
Results: The adductor longus, brevis, rectus abdominis and pyramidalis muscles are attached to the anterior pubic ligament (APL). The adductor brevis and gracilis muscle are connected to the inferior pubic ligament (IPL). The IPL and superior pubic ligament (SPL) are thicker than the APL and posterior pubic ligament (PPL). The PPL is the thinnest pubic ligament. The APL has a larger sagittal area in women than in men compared to the IPL. The SPL and IPL are thicker in men compared to women.
Conclusion: The APL is the ligamentous anchor for the originating and inserting muscles. Investigations of the pubic ligaments might help to determine symphysis instability or severity of injury and should be included as a further criterion for surgical management.

1. Introduction

Groin injuries belong to the top three injuries in football (Ekstrand et al., 2011; de Sa et al., 2016; Arnason et al., 2004) and are classified as adductor-, inguinal- and pubic- related pain, differing in their provocation tests and location (Weir et al., 2015).

A clinical anatomical-based examination has been asked to differentiate the cause of groin pain (de Sa et al., 2016; Falvey et al., 2009). Adductor-related groin pain is present by adductor tenderness and pain on resisted adduction testing (Weir et al., 2015). Inguinal-related groin pain is described as a pain sensation at the inguinal canal region without a palpable inguinal hernia but with tenderness of the inguinal canal (Weir et al., 2015). It might be intensified by resistance testing of the abdominal muscles. Pubic-related groin pain is characterized by local tenderness of the symphysis pubis and the surrounding bony structures (Weir et al., 2015). However, there is no specific provocation test for pubic-related groin pain. It was generally interpreted in terms of muscular injuries but recent reports even highlight the role and involvement of the pubic ligaments (Morgan et al., 2019; Mathieu et al., 2019). Anatomical results to date seem partly inconsistent due to differing topographical descriptions of the symphysis pubis (Robertson et al., 2009; Norton-Old et al., 2013; Robinson et al., 2007; Maeseneer et al., 2019; Schilders et al., 2017; Becker et al., 2010; Gamble et al., 1986). This controversy might be due to the individual observations in layered dissection and small sample sizes used (Robertson et al., 2009; Norton-Old et al., 2013; Robinson et al., 2007; Schilders et al., 2017; Gamble et al., 1986). Noteworthy, most cases of groin pathologies require surgery and besides femoroacetabular impingement pubic pathologies represent the second main group of patients subjected to surgical interventions (de Sa et al., 2016). Although an open procedure was chosen for pubic pathologies, standardized procedures have not been established yet (de Sa et al., 2016). The missing secured anatomical description probably led to

Abbreviations: APL, Anterior pubic ligament; IPL, Inferior pubic ligament; SPL, Superior pubic ligament; PPL, Posterior pubic ligament; MRI, Magnetic resonance imaging; PAS, Periodic acid-Schiff; SD, Standard deviation.

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https://doi.org/10.1016/j.aanat.2021.151698

the establishment of homemade treatment algorithms (Schilders et al., 2017). To overcome such problems, a distinct anatomical description is required, and additionally the pubic ligaments should be considered as contributing structures to pubic groin pain apart from muscular injuries.

In the current Terminologica Anatomica (Federative Committee on Anatomical Terminology, 1998) only the superior and inferior pubic ligaments are described. Nevertheless, there are four pubic ligaments (Fick, 1904; Becker et al., 2010) (Fig. 1). The superior pubic ligament (SPL) is spanned superiorly to the joint between the pubic tubercles and attached to the pubic crest (Becker et al., 2010). The inferior pubic ligament (IPL) – also known as arcuate pubic ligament – is an arch bridging the inferior parts of the pubic rami. The anterior pubic ligament (APL) with differing fibre orientation lays anteriorly and is connected to the periosteum of the pubic bones. The posterior pubic ligament (PPL) is a thin ligament at the posterior portion of the symphysis pubis, blending into the periosteum, SPL and IPL. Data on their length, width and thickness are sparse (Becker et al., 2010).

Although predominantly men suffer from groin pain, in women, too, the pubic ligaments have a pivotal role e.g. considering postpartum symphyseal disruptions (Osterhoff et al., 2012).

The present study purposed to determine the topography of the symphysis pubis in relation to their four ligaments (Fick, 1904; Becker et al., 2010), combining gross anatomical approaches (layered dissection, midline transected hemipelves, plastinated body slices) (Maeseneer et al., 2019; Hunter et al., 2019; Steinke et al., 2010; Steinke, 2001; Steinke and Rowedder, 2018; Steinke et al., 2018, 2008). Secondly, the sagittal and coronal area, width, length and thickness of the pubic ligaments were measured. Thirdly, gender-specific differences were examined to identify possible structural reasons for the predominance of groin pain in men. Female samples were therefore declared as control group. Hereby, we aimed to highlight the pubic ligaments as an essential structure for investigation of groin pain especially in the evaluation of radiological examinations.

2. Material and methods

Pelves were collected from human donors after their death. All donors had signed informed consent for body donation for education and medical research during life. The study was performed according to Japanese law ("Act on Body Donation for Medical and Dental Education") and approved by the Tokyo Medical University, Institutional Review Board (approval number: T2020−0050) or in accordance with the institutional approval of the Institute of Anatomy, University of Leipzig, for the use of post- mortem tissues, which is part of the body donation program, regulated by the Saxonian Death and Funeral Act of 1994 (third section, paragraph 18 item 8). Signed consents are available on reasonable request from HS and MI. Sixty formaldehyde-embalmed hemipelves (mean age, 81.9 years; range, 58–105 years; left and right each 30; 14 males, 16 females, Supplemental Table 1) and 10 layered dissected formaldehyde-embalmed cadavers (mean age, 82.8 years; range, 55–102 years; 6 males, 4 females, Supplemental Table 2) were examined. There was no evidence for previous surgery or injury at the symphyseal region. Photographs were taken with a pentax k-5-II. Measurements were performed with ImageJ (ImageJ 1.43, imagej.nih.gov/ij/) (Pieroh et al., 2019). Based on the image resolution a theoretical accuracy of 0.03 mm was determined.

2.1. Hemipelves- topography and sagittal measurements

The surrounding soft tissue was removed, and a classical midline transection was performed during the medical dissection course prior to the study (Steinke et al., 2010).

We incised the adductor longus, brevis and gracilis periosteally either coronally or sagittally to their origin revealing their connection to the pubic ligaments. The external and internal obturator muscles were exposed to examine their connection to the pubic ligaments. Posteriorly, the attachments of the bladder or prostate were investigated. A straight sagittal photograph with a vernier caliper as reference was taken for quantitative analyses of the sagittal plane (Supplemental Fig. 1 A). The sagittal pubic ligament area in immediate connection to the bone (Fig. 1 G and H, Supplemental Fig. 1 A and Supplemental Fig. 3 A) and maximum thickness, measured at one point, were determined (Supplemental Fig. 1 A).

2.2. Layered dissection ("tissue sample")- Topography and coronal measurements

Dissection was performed as a combination of outside-in and inside-out layered dissection using a Stoppa approach with additional extensions to the proximal femur. The rectus abdominis and pyramidalis muscles were exposed. The rectus abdominis was cut and flapped caudally. Posteriorly, the bladder was retracted to visualize the pubovesical/puboprostatic ligament and the PPL. Anteriorly, the soft tissue was removed. Starting from the pectineal muscle, the periosteum was completely removed following a separation of the PPL and SPL. The PPL was cut at the border to the SPL and IPL and removed (Supplemental Fig. 2 A). Muscles were cut approximately 10 cm distally from their origin (Supplemental Fig. 2 B). The remaining pubic ligaments including the origins of the released muscles were mobilized (Supplemental Fig. 2 C) and completely removed from the bony pelvis. The obtained sample is named "tissue sample" (Supplemental Fig. 2 D).

Each muscle was separately resected and photographically documented. From superficial to the deep, each muscle was resected until only the pubic ligaments were left. Needles were placed at the macroscopical visible borders of the pubic ligaments (Supplemental Fig. 1 B and Supplemental Fig. 3 B and C). A vernier caliper was applied, and the ligaments were analysed ventrally and posteriorly to determine their length and width. Thickness was measured at three arbitrarily set points (Supplemental Fig. 1 B). In contrast to the sagittal thickness, the coronal thickness was calculated as the mean of at least two measurements. For the length and width, measurements were performed at least at five points. The area of each ligament was calculated and used for further analyses.

2.3. Plastinated body slices

Plastinated body slices of three body donors (Supplemental Table 3) were utilized. Three pelves including the proximal femora were pre-cooled at 3 °C and subsequently frozen at −85 °C in 85% acetone (Dr. Hollborn und Söhne, Leipzig, Germany). Slices with a thickness of 1−2 mm were obtained by application of a stationary band saw (HL 30, Biodur, Heidelberg, Germany) equipped with a 10 mm sawing band (Otto Lange, Leipzig, Germany) placed at −20 °C (Steinke, 2001; Steinke et al., 2018). Slices were put in wire framed chests (Biodur), separated with polyester meshes (Biodur) and stored at −25 °C. The specimens were dehydrated with 100% acetone for 4–6 weeks, the solution thrice renewed. The sagittally cut pelvis was left unstained. The axially cut pelvis was stained with methylene blue (Steinke et al., 2008). Slices were placed in distilled water containing 0.5% (w/v) sodium carbonate (Sigma-Aldrich, Darmstadt, Germany), 0.0125% (w/v) methylene blue (Alfa Aesar Methylene blue, Thermo Fischer GmbH, Kandel, Germany) and 0.0125% (w/v) Azur A (pH = 7.9–8.7; Sigma-Aldrich) for three minutes. Subsequently, slices were transferred to acetone (Roth GmbH, Karlsruhe, Germany) containing 15% (v/v) distilled water and 0.03% (v/v) hydrochloric acid (pH = 2.2–2.4; PanReac, Applichen GmbH, Darmstadt, Germany) for one minute to differentiate the

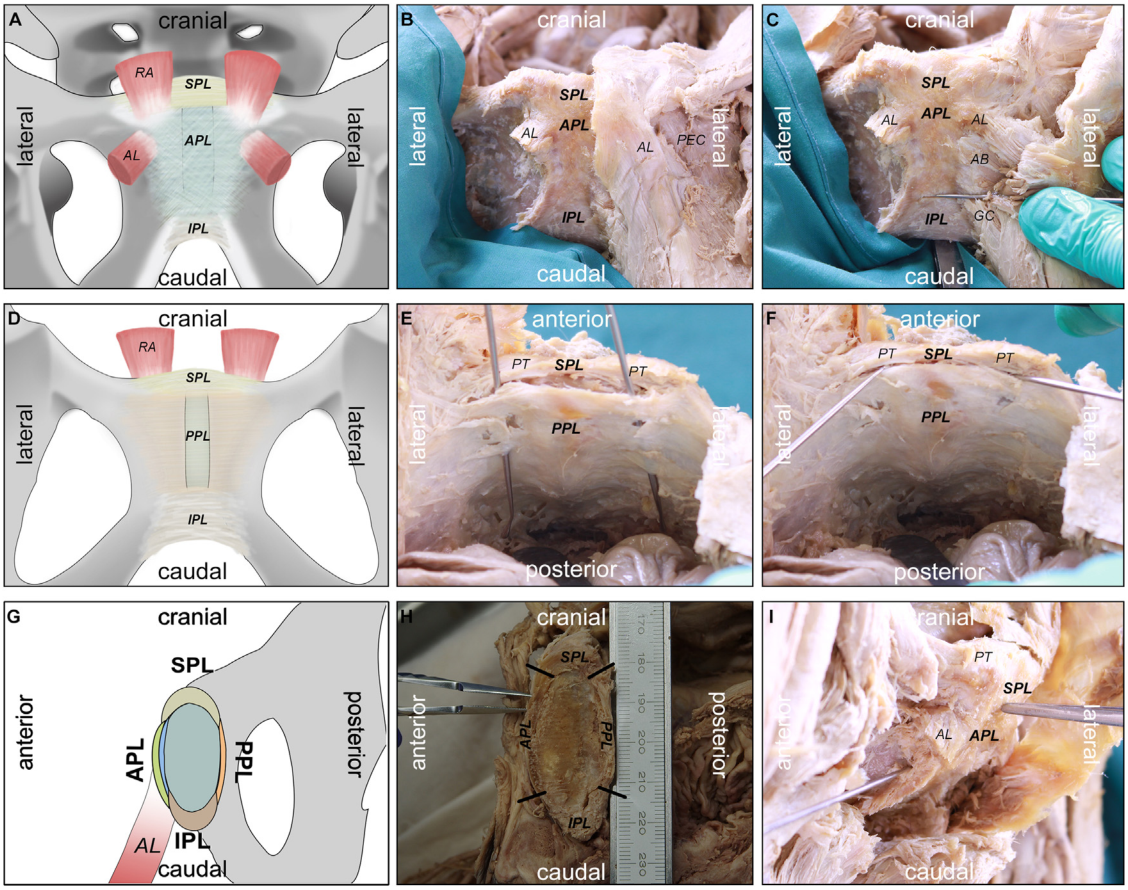

Fig. 1. Overview of the pubic ligaments. Coronal outlet view (A–C): The superior pubic ligament (SPL), spanned between the pubic tubercles (PT) and the inferior pubic ligament (IPL) is noticed as an arch between the inferior parts of the pubic rami. Anteriorly, the rectus abdominis (RA) inserts at the anterior pubic ligament (APL) and connects to the adductor longus (AL) as highlighted in Fig. 4. Noteworthy, even superficially several fibres of the fasciae and surrounding muscles blend into the APL (B). After their removal (C) the connections of the APL to the AL, adductor brevis muscle (AB) and of the IPL to the AB and gracilis muscle (GC) are revealed. In the posterior inlet view (D-F) the posterior pubic ligament lies over the symphyseal disc blending into the periosteum. Furthermore, the SPL as a connection between the PT is highlighted. In the sagittal view (G,H) and parasagittal view (I) the differing thicknesses of the pubic ligaments are shown. In picture I the thickness of the APL is highlighted by the probe inserted. PEC pectineus muscle; GC gracilis muscle.

staining before they were stored in 100% acetone (1–90 days). The coronally cut pelvis was stained by the periodic acid-Schiff (PAS) reaction (Steinke et al., 2018). Slices were stained with acetone containing 0.5% (v/v) periodic acid (Roth, Karlsruhe, Germany) for 15 min. In the following, they were rinsed in acetone before being placed in Schiff reagent (Dr. Hollborn und Söhne, Leipzig, Germany) for one minute. Subsequently, slices were subjected to distilled water containing 47% (v/v) acetone and 6% (w/v) potassium bisulfite solution and then rinsed and stored in 100% acetone. All slices were plastinated using epoxy resin (E12/E1, Biodur, Heidelberg, Germany) and embedded with the sandwich technique (Hagens, 1985). Musculotendinous connections stained with methylene blue appear in blue (Steinke et al., 2008), and in PAS staining red/purple. Muscles remain unstained in both labelling techniques (Steinke et al., 2018).

2.4. Statistical analyses

Data are presented as mean ± standard deviation (SD) and range. A Gaussian distribution was determined for the coronal pubic ligament area, pubic ligament thickness from coronal measurements, width and length by using the Shapiro-Wilk test. We analysed these parameters using a one-way ANOVA with post-hoc Bonferroni correction. The maximum pubic ligament thickness and area in the sagittal plane were non-Gaussian distributed. Therefore, the Mann-Whitney or Kruskal- Wallis test were applied followed by Dunn's multiple comparison test for analyses. Gender-specific differences were investigated with a two-way ANOVA with post-hoc Bonferroni correction. The level of significance was defined with $p < 0.05$. Analyses were done with Graph Pad Prism software 7 (GraphPad software, La Jolla, USA).

3. Results

All pubic ligaments had a direct connection to the symphyseal disc. The SPL and IPL showed a triangular shape with a small surface area, whereas the APL and PPL were flat with a large surface area (Fig. 1).

3.1. Topography of the pubic ligaments

The adductor longus muscle is connected to the APL (Figs. 1 and 2). In 25/60 hemipelves the tendon and in 35/60 muscle fibres of the adductor longus reached the APL. The rectus abdominis and pyramidalis muscles were connected to the APL without any contact to the SPL (Fig. 2). The adductor brevis muscle originated at the APL and at the IPL and strengthened the adductor longus muscle (Figs. 1 and 3). The gracilis muscle was connected to the IPL (Figs. 1 and 3). The adductor brevis and gracilis muscles were interlaced but had their own origins. The PPL and posterior part of the IPL interlaced with the lateral pubovesical or puboprostatic ligament (Fig. 3). The obturatorius internus and externus muscles

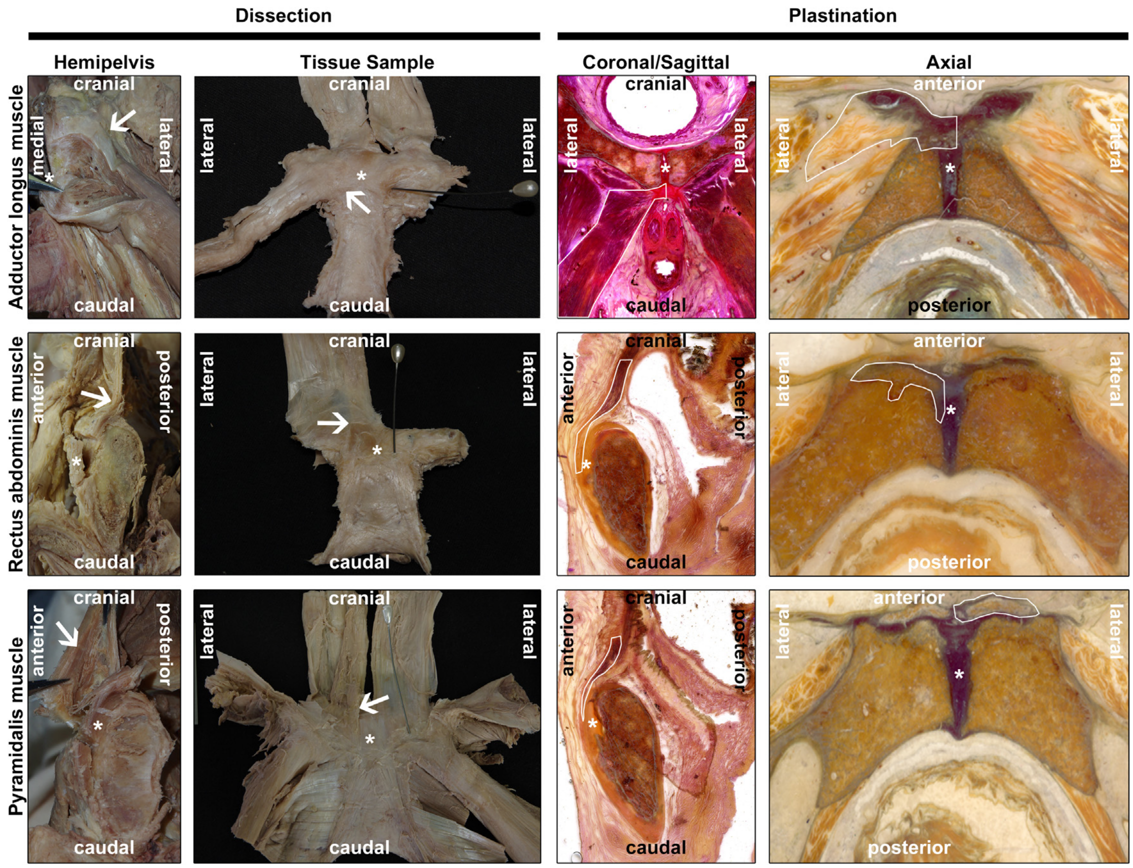

Fig. 2. Connections of the adductor longus, rectus abdominis and pyramidalis muscle to the pubic ligaments in hemipelvis, resected tissue sample and plastinated specimen. Plastinated body slices: coronally cut - periodic-acid Schiff [PAS] reaction stained- musculotendinous connections are red/purple; sagittally cut - unstained- musculotendinous connections are unstained; axially cut - methylene blue stained- musculotendinous connections are blue. Asterisk marks the symphysis pubis. An arrow marks the examined muscles in hemipelvis and "tissue sample". A frame marks the analysed muscle in plastinated body slices. In the tissue sample, needles label the muscle attachment after removal of the respective muscles. Contralaterally, the muscle is marked by an arrow.
The adductor longus and rectus abdominis are connected to the deep layers of the APL. The pyramidalis muscle has superficial connections to the APL. Between the rectus abdominis and pyramidalis muscles a separating fascia is stained in axially cut body slices.

were not connected to the pubic ligaments (data not shown). No gender-specific differences were observed.

3.2. The layered organization of the APL underlining the complex anatomy of the groin

Superficially, the pyramidalis muscle laid on the rectus abdominis and attached to the APL and inguinal ligament (Fig. 4 A). Thin fibres of the pyramidalis were connected to the adductor longus (Fig. 4 B). The pyramidalis and rectus abdominis muscles were separated by a fascia (Fig. 2, axial plastination). The rectus abdominis muscle was fully exposed after mobilizing the pyramidalis muscle and releasing the fascia (Fig. 4 C). The rectus abdominis and adductor longus muscles reached and strengthened the APL directly in the deep of the ligament (Fig. 4 D).

3.3. Morphometric investigation of the pubic ligaments – measurements on hemipelves

Due to the destruction of either one or multiple pubic ligaments, three hemipelves were partially or completely excluded from measurements (Table 1).

The PPL showed significantly lower values in its maximum thickness and displayed the smallest sagittal area compared to the SPL, IPL and APL ($p < 0.0001$ for each comparison; Table 1). The SPL and IPL were thicker than the APL (SPL vs. APL, $p = 0.0021$; IPL vs. APL, $p = 0.0002$). The SPL and IPL did not differ in their maximum thickness ($p > 0.9999$). Partial gender-specific differences were detected. The SPL and IPL were thicker in men than in women (SPL: male vs. female, $p = 0.0494$; IPL: male vs. female, $p = 0.0005$). The sagittal area of the APL was larger than the area of the IPL ($p < 0.0257$). Notably, this difference was found in women only (male: APL vs. IPL, $p > 0.9999$; female: APL vs. IPL, $p = 0.0141$). The sagittal area of the SPL did not significantly differ from the APL and IPL ($p > 0.05$).

3.4. Morphometric investigation of the pubic ligaments – measurements in layered dissected cadavers

One PPL was partially and another one completely excluded from the study. In one case the PPL was destroyed, and in another one it was ruptured during the thickness measurement. Detailed values on width, length, thickness and coronal area measurements are summarized in Table 2.

The pubic ligaments did not differ in their width ($p > 0.05$ for each comparison). The APL and PPL were significantly longer than the SPL and IPL ($p < 0.0001$ for each comparison). The APL was significantly longer than the PPL ($p = 0.0226$). The SPL and IPL did not differ in their length ($p > 0.05$). The PPL was thinner compared to the SPL, IPL and APL (PPL vs. SPL, $p = 0.0025$; PPL vs. APL and PPL vs. IPL, $p < 0.0001$). The APL, SPL and IPL yielded no difference in their mean thickness ($p > 0.05$). The coronal area of the APL and PPL was larger than of the SPL and IPL (APL vs. SPL, $p = 0.0042$; APL vs. IPL, $p = 0.0008$; PPL vs. SPL, $p = 0.0004$; PPL vs. IPL, $p < 0.0001$). The APL

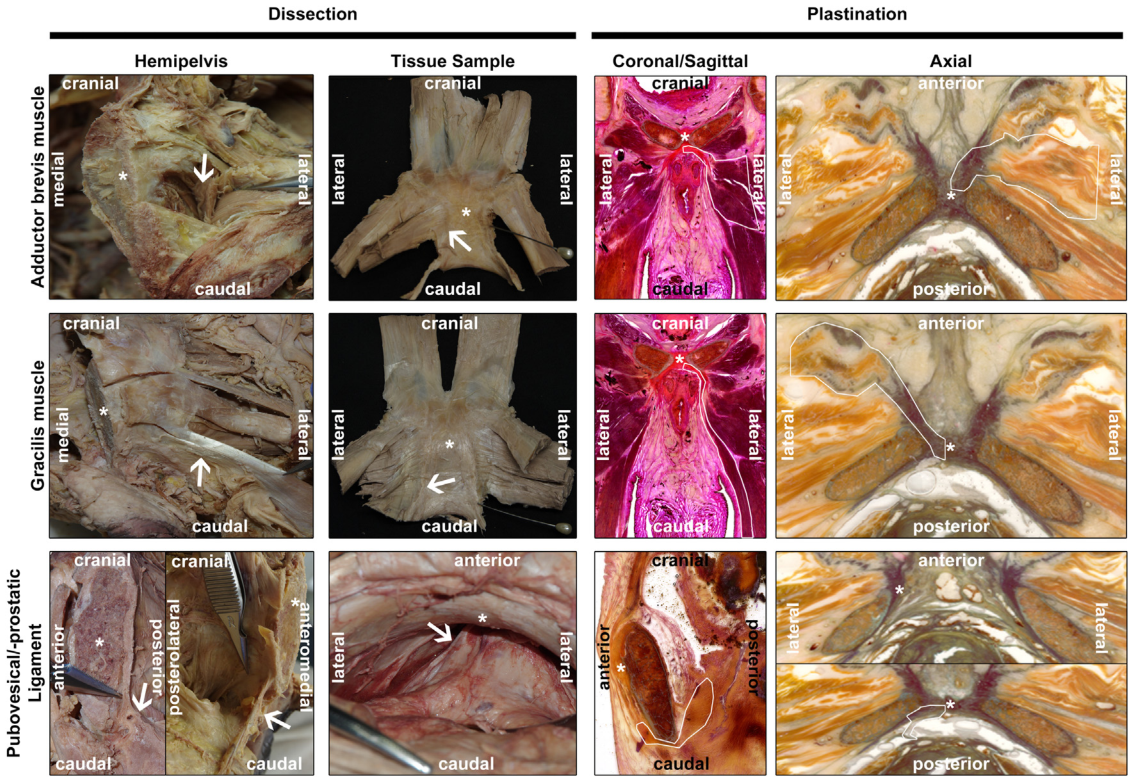

Fig. 3. Connections of the adductor brevis, gracilis muscle and the pubovesical/-prostatic ligament to the pubic ligaments in hemipelvis, resected tissue sample and plastinated specimen.
Plastinated body slices: coronally cut - periodic-acid Schiff [PAS] reaction stained- musculotendinous connections are red/purple; sagittally cut - unstained- musculotendinous connections are unstained; axially cut - methylene blue stained- musculotendinous connections are blue. Asterisk marks the symphysis pubis. An arrow marks the examined muscles in hemipelvis and "tissue sample". A frame marks the analysed muscle in plastinated body slices. In the tissue sample, needles label the muscle attachment after removal of the respective muscles. Contralaterally, the muscle is marked by an arrow.
The adductor brevis is attached to the APL and to the IPL. The gracilis muscle is connected to the IPL. The IPL and posterior pubic ligament are connected to the lateral pubovesical/puboprostatic ligament.

Table 1
Measurements of the pubic ligaments in the sagittal plane in hemipelves including gender-specific analyses. Data are presented as mean ± standard deviation (SD) and range. n = number of investigated samples. SPL: superior pubic ligament; APL: anterior pubic ligament; IPL: inferior pubic ligament; PPL: posterior pubic ligament.

Sagittal Measurements	Maximum Thickness [mm]		Area [mm^2]		n
	mean ± SD	*range*	*mean ± SD*	*range*	
SPL					
all	6.92 ± 2.19	(2.51–12.26)	101.90 ± 32.67	(45.19–185.80)	59
male	7.79 ± 2.32	(2.51–12.26)	110.80 ± 33.92	(45.19–185.8)	27
female	6.18 ± 1.79	(2.53–10.15)	94.44 ± 30.10	(55.32–182.30)	32
APL					
all	5.00 ± 1.58	(2.66–9.63)	110.20 ± 42.18	(43.23–250.50)	58
male	5.23 ± 1.56	(3.15–8.53)	116.70 ± 45.53	(50.67–250.50)	27
female	4.81 ± 1.58	(2.66–9.63)	104.60 ± 38.91	(43.23–208.00)	31
IPL					
all	7.59 ± 3.03	(1.70–15.61)	86.94 ± 36.63	(19.07–207.30)	59
male	8.80 ± 3.44	(2.39–15-61)	100.60 ± 41.43	(42.11–207.30)	27
female	6.58 ± 2.23	(1.70–10.71)	75.38 ± 27.75	(19.07–136.80)	32
PPL					
all	1.51 ± 0.51	(0.72–3,19)	45.60 ± 17.76	(19.02–104.60)	58
male	1.40 ± 0.49	(0,72–3.19)	45.57 ± 14.44	(23.39–76.68)	26
female	1.59 ± 0.52	(0.74–2.67)	45.62 ± 20.29	(19.02–104.60)	32

Table 2
Measurements of the pubic ligaments in layered dissected cadavers ("tissue sample"). Width, length and mean thickness were measured at least at five points in at least one photograph to calculate the mean value. The coronal area was measured in each available photograph. Data are presented with mean ± standard deviation (SD) and the range. n = number of investigated samples. SPL: superior pubic ligament; APL: anterior pubic ligament; IPL: inferior pubic ligament; PPL: posterior pubic ligament.

Coronal Measurements	Width [mm]		Length [mm]		Thickness [mm]		Area [mm^2]		n
	mean ± SD	*range*	*mean ± SD*	*range*	*mean ± SD*	*range*	*mean ± SD*	*range*	
SPL	27.67 ± 5.79	(19.76–35.39)	15.95 ± 3.80	(11.21–23.60)	3.94 ± 1.00	(2.60–5.94)	494.00 ± 115.90	(315.80–657.70)	10
APL	24.52 ± 3.78	(19.10–29.20)	30.74 ± 3.67	(25.77–38.08)	4.56 ± 0.74	(3.22–5.63)	763.20 ± 107.60	(583.80–939.70)	10
IPL	28.96 ± 7.00	(17.18–39.28)	14.41 ± 2.85	(10.78–20.10)	4.47 ± 1.07	(3.29–6.83)	452.40 ± 136.4	(275.30–672.90)	10
PPL	22.68 ± 5.31	(15.13–33.23)	37.34 ± 7.28	(26.03–48.94)	2.25 ± 0.77	(1.29–3.81)	828.90 ± 256.60	(608.50–1366.00)	9 (8)

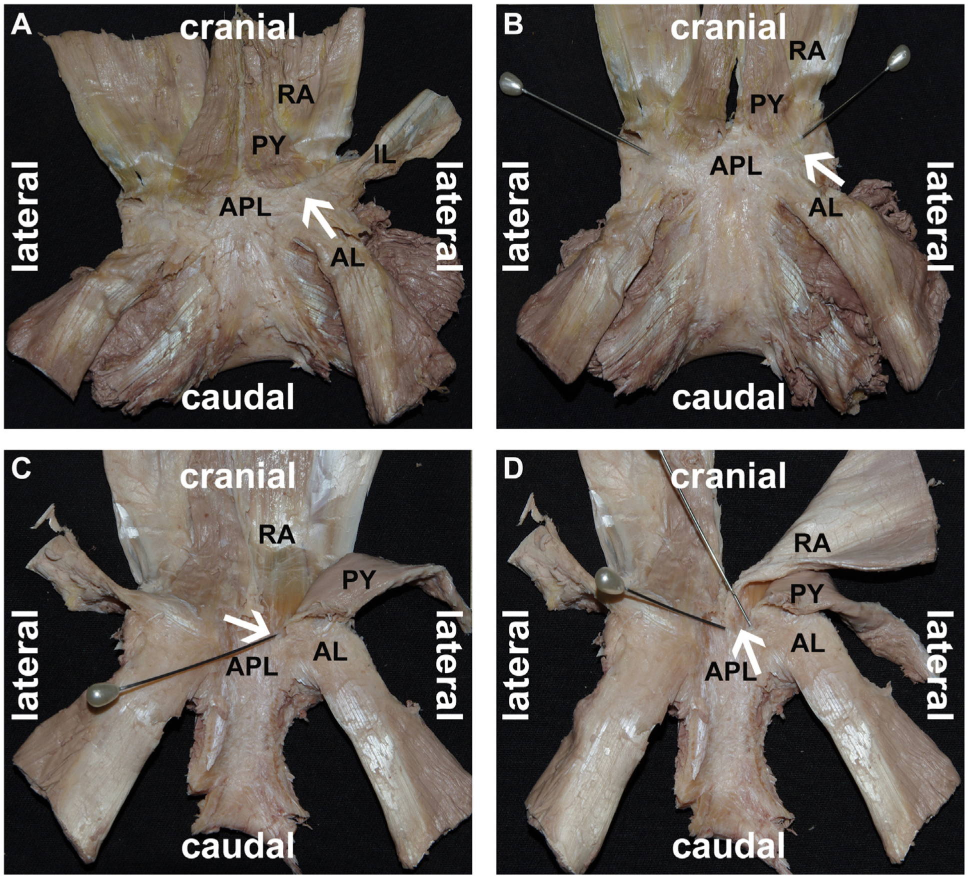

Fig. 4. The layered organization at the anterior pubic ligament.
A The pyramidalis muscle lies on the rectus abdominis muscle and connects superficially to the inguinal ligament and APL, as indicated by an arrow.
B After removing the inguinal ligament, the superficial connections of the pyramidalis and adductor longus are revealed (arrow).
C The lateralization of the pyramidalis muscle shows the separating fascia between the pyramidalis and rectus abdominis (needle, arrow). A release of the pyramidalis muscle does not harm the integrity of the APL.
D The rectus abdominis is deeply connected to APL and adductor longus (arrow).
APL: anterior pubic ligament; RA: rectus abdominis; PY: pyramidalis muscle; IL: inguinal ligament; AL: adductor longus.

and PPL as well as the SPL and IPL did not significantly differ in their coronal area (APL vs. PPL, $p > 0.9999$; SPL vs. IPL, $p > 0.9999$).

4. Discussion

In the present study we combined the gross anatomical approaches of layered dissection, hemipelvis investigation and (un)stained plastinated body slices and described the layered topography of the symphysis pubis and their ligaments in a high number of cadavers (n = 43). Our data highlight the role of the APL and IPL as an anchor for muscle origins and insertions. Morphometric data suggest a more stabilizing effect of the SPL and IPL. Furthermore, the layered organization of the APL in relation to the originating and attaching muscles underline the pivotal part of this ligament in force transmission.

The pubic ligaments SPL, IPL, PPL and APL surround the symphysis pubis (Fick, 1904; Becker et al., 2010) (Fig. 1). Apart from the connections of the SPL, IPL and APL to the interpubic disc, we found a connection between the PPL and the disc (Becker et al., 2010). Whereas a recent report doubted the PPL is a separate structure, we observed the PPL as a separate ligament strengthening the pubic periosteum and connected to the lateral pubovesical or puboprostatic ligament, as reported previously (Xu et al., 2017; Kim et al., 2014).

On the contrary, the APL was extensively investigated due to its relation to the surrounding muscles. Anatomical text books as well as earlier publications reported on connections of the APL and the adductor longus and brevis, gracilis, rectus abdominis, pyramidalis and oblique abdominal muscles (Fick, 1904; Becker et al., 2010; Gamble et al., 1986). The APL connected the inguinal ligament and adductor longus muscle as well as the adductor longus and rectus abdominis muscle (Norton-Old et al., 2013; Robinson et al., 2007; Maeseneer et al., 2019; Schilders et al., 2017; Schilders, 2000; Condon, 1996; Davis et al., 2012). Supporting the abovementioned findings, we observed these connections and described their layered organization. Superficially, the inguinal ligament was connected to the adductor longus muscle through the APL and in the deep the adductor longus muscle is connected to the rectus abdominis muscle, which is in line with a previous report on sectioned cadavers (Maeseneer et al., 2019). We confirmed the presence of a separating fascia between the rectus abdominis and pyramidalis (Maeseneer et al., 2019; Schilders et al., 2017).

Recently, a connection of the rectus abdominis muscle was described to the SPL and denied to the APL, and the pyramidalis muscle was assumed as the only non-oblique abdominal muscle attaching to the APL (Schilders et al., 2017). But so far, an earlier work of that group and the here obtained results as well as recent reports contradict this hypothesis (Robinson et al., 2007; Maeseneer et al., 2019; Schilders et al., 2017; Schilders, 2000; Davis et al., 2012). We could not confirm a previous report describing the existence of a recto-gracilis tendon in men only (Schilders, 2000).

Although the adductor brevis muscle was described originating from the pubic ligament its precise origin remained unclear (Robinson et al., 2007; Maeseneer et al., 2019). The origin of adductor brevis muscle was found in this study at the APL as well as the IPL. Whereas the gracilis muscle originated at the IPL in all specimens of our study, this was reported in only 41% of specimens previously examined (Robinson et al., 2007). Additionally, we determined the fusing of the adductor brevis and gracilis muscle as earlier stated (Davis et al., 2012). Probably, the poor description of the layered organization, individual observations during dissection, the use of confusing terms like symphysis pubis capsular tissue and limited sample size led to the conflicting results in the topographical description (Norton-Old et al., 2013; Robinson et al., 2007; Maeseneer et al., 2019; Schilders et al., 2017; Gamble et al., 1986; Davis et al., 2012).

The IPL was defined as a major stabilizer of the symphysis pubis (Gamble et al., 1986). Due to the thickness and muscle connections as well as layered differing fibre orientation the APL was supposed as a key stabilizer (Robertson et al., 2009; Becker et al., 2010; Ibrahim and El-Sherbini, 1961).

The IPL was reported with a width of 35 mm in women and 25 mm in men, a height of 10–12 mm and a mean thickness of 5–12 mm (Becker et al., 2010). Although the data acquisition was not described and the results were obtained from anatomical textbooks and summarized, they are in accordance to ours (Becker et al., 2010). Another publication reported on a thickness of 1 cm for the APL, which is quite high in comparison to our data (Maeseneer et al., 2019).

In former studies, a higher thickness of the IPL compared to the SPL was suggested but not found in our study (Becker et al., 2010; Ibrahim and El-Sherbini, 1961). Notably, both ligaments were significantly thicker in men than in women. The APL shows a large sagittal and coronal area which is probably responsible for its high capacity to withstand horizontal stress (Ibrahim and El-Sherbini, 1961). Noteworthy, in women the sagittal area of the APL is significantly larger compared to the IPL. Further studies will be needed to investigate the changes and differences in pubic ligament size with regard to pathologies such as pubic-related groin pain.

Even in pathologies such as femoroacetabular impingement the reduced motion of the hip joint results in a secondary opening of the symphysis pubis and high stress levels for the APL especially in the transverse plane (Birmingham et al., 2012). The lower thickness of the APL compared to the SPL and IPL might explain the higher force needed to induce and to maximize vertical compared to horizontal displacement (Meissner et al., 1996).

We highlighted the topography of the anatomy and the role of the APL as an anchor for several originating and inserting muscles. Biomechanical considerations suggest a role of the APL in horizontal and for the IPL and SPL in vertical joint stabilization as underlined by the here-obtained morphometric data. Probably, this data will lead to further biomechanical as well as radiological investigations. Here, possible symphyseal instabilities might be detected by evaluating the pubic ligaments, especially in the context of superior and secondary cleft signs (Brennan et al., 2005; Byrne et al., 2017). Thus, the diagnostic accuracy regarding symphyseal instability or severity of injury could be improved. Analysing the pubic ligaments will allow to differentiate between asymptomatic and symptomatic findings and assist for the therapeutic decision making.

The topography of the conjoint tendon, Scarpa's, Camper's fascia, Cooper's ligament, arcus tendineus m. levator ani and arcus tendineus fasciae pelvis were not examined (Robertson et al., 2009; Steinke and Rowedder, 2018; Condon, 1996). Although other studies emphasized the use of fresh-frozen cadavers because of alterations in topographical anatomy in embalmed fixed specimen, to the authors' knowledge such differences were not described (Schilders et al., 2017). Embalming might shrink the tissue leading to an underestimation of the morphometric results of the pubic ligaments (Steinke et al., 2012; Brenner, 2014). The age of the specimen and missing information on their physical activity might impair the morphometric data.

Furthermore, data on the physical activity and radiological findings would allow a more detailed interpretation of the here presented results. Unfortunately, this information was not delivered to the anatomical departments. In addition, data of younger people would be interesting, but presumably they would be difficult to compare to the presented data. Probably, the study will benefit from histological examinations. The authors believe the stained sections are an equivalent attempt to show the topography, especially regarding the investigated area.

Ethical statement

Pelves were collected from cadavers who signed informed consent for agreement for body donation for education and medical research during life. The study was performed accordingly to the Japanese law ("Act on Body Donation for Medical and Dental Education") and approved by the Tokyo Medical University, Institutional Review Board (approval number: T2020–0050) or in accordance to the institutional approval of the Institute of Anatomy, University of Leipzig for the use of post- mortem tissues which is part of the body donation program, regulated by the Saxonian Death and Funeral Act of 1994 (third section, paragraph 18 item 8). Signed consents are available on reasonable request from HS and MI.

Funding

The present study was funded by the Ichiro Kanehara Foundation with the Chihiro andKiyoko Yokochi Fund.

Competing interest

The Ichiro Kanehara Foundation had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results. The authors declare no further conflict of interest.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the first author on reasonable request.

CRediT authorship contribution statement

Philipp Pieroh: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Writing - review & editing. **Zhong-Lian Li:** Methodology, Investigation, Writing - review & editing. **Shinichi Kawata:** Methodology, Investigation, Writing - review & editing. **Yuki Ogawa:** Resources, Validation, Writing - review & editing. **Christoph Josten:** Supervision, Project administration, Writing - review & editing. **Hanno Steinke:** Conceptualization, Methodology, Validation, Supervision, Writing - review & editing. **Faramarz Dehghani:** Conceptualization, Validation, Data curation, Supervision, Writing - original draft, Visualization, Writing - review & editing. **Masahiro Itoh:** Conceptualization, Methodology, Resources, Validation, Supervision, Writing - review & editing.

Acknowledgments

The authors would like to thank the Ichiro Kanehara Foundation for funding, Dr. med. Mara Sandrock for the schematic illustrations of Fig. 1 and Hidenobu Miyaso, Kenta Nagahori, Takuya Omotehara for their help and interesting discussions.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aanat.2021.151698.

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