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Enhanced Biomechanical Properties of the Pectineal Ligament Support Its Reliability for Apical Pelvic Organ Prolapse Repair

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Abstract: Pelvic organ prolapse impacts an increasing number of women in the United States. The standard approach to correcting apical pelvic organ prolapse uses the sacral anterior longitudinal ligament (SALL) to lift the vaginal apex; however, this approach may result in recurrent prolapse. A newer procedure utilizes the pectineal ligament (PL), which may be a more reliable anchor point. This study compares the biomechanical properties of these two ligaments to elucidate which can withstand more stress to provide long-term stability following prolapse. Seventeen formalin-embalmed donors were used (PL: 17 right, 16 left; SALL, 15). The PL was evaluated to better characterize the ligament's properties within the pelvis using digital calipers and descriptive statistics. Mean values were statistically evaluated using an independent *t* test ($p = 0.05$) but no differences in laterality were appreciable. The PL and SALL samples were harvested and evaluated using a mechanical tester to determine their force at failure (N), toughness (Jm^{-2}), and elastic modulus (MPa). The PL had increased values in the mean force at failure and toughness than the SALL when evaluated by each side as well as a combined mean value. These differences were statistically significant ($p = 0.05$) for toughness as evaluated using an independent *t*-test (right, $p = 0.004$; left, $p = 0.005$; combined, $p = 0.002$) and force at failure [right, $p = 0.001$ (independent *t*-test); left, $p = 0.004$ and combined, $p = 0.005$ (Mann–Whitney U test)], indicating that the PL may permit more deformation, but greater resistance to catastrophic failure as compared to the SALL. When evaluating any statistical differences in modulus, the individual and combined values were increased for the PL as compared to the SALL but were not significant (right, $p = 0.290$; left, $p = 0.143$; combined, $p = 0.110$) suggesting a stiffer material that may be more prone to catastrophic failure once a tear has begun. Collectively, these inherent biomechanical properties of the pectineal ligament indicate the ligament may be a more reliable anchor point for pelvic organ prolapse repair than the SALL.

Keywords: iliopectineal ligament; apical pelvic organ prolapse; biomechanical properties

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1. Introduction

Pelvic organ prolapse is the descent of one or more aspects of the uterus and vagina, resulting in vaginal bulging, dyspareunia, and pelvic pain [1,2]. Although prolapse is not considered life-threatening, it can cause nearby organs to herniate into the vaginal space, resulting in a cystocele, rectocele, or enteroceles that severely impacts the patient's quality of life [2]. Apical pelvic organ prolapse, the focus of this research, occurs when the vaginal vault (cuff) that remains after a woman has a hysterectomy droops [1]. Women with apical prolapse experience additional bladder and bowel dysfunction, including urinary retention or incontinence, obstructed voiding, and fecal urgency or incontinence [1].

After attempting non-surgical options such as pessaries and manual reduction, definitive management of pelvic organ prolapse requires surgical intervention [2]. According to the American College of Obstetrics and Gynecologists Practice Bulletin [2], women in the United States have a lifetime risk of 13% for requiring prolapse surgery. Due to the aging population who experience weakening of the pelvic floor with age, this number is expected to increase to over 50% by 2050. Although more likely in older individuals, other risk factors include obesity, increased parity, chronic constipation, and connective tissue disorders [2]. One of the most widely used approaches to correct apical prolapse surgically is sacrocolpopexy. This procedure lifts the vaginal apex via mesh fixation to the anterior longitudinal ligament of the sacrum (SALL) [3]. While this method is the "gold standard" for prolapse repair [3,4], research indicates the position of the mesh attachment to the sacrum creates a narrowing of the pelvic cavity [1,3,5]. This constriction results in defecation disorders, ileus, stress urinary incontinence, and adhesion formation [1,5]. Additionally, this procedure has a recurrence rate of 30–50% [6,7].

Laparoscopic pectopexy is a relatively new technique for prolapse repair, recently described by Banerjee and Noe [8], utilizing the pectineal ligament as compared to the SALL. The technique was initially characterized in an open-abdominal approach by Joshi [9] and has experienced increased utility as an alternative for patients with challenging pelvic organ prolapse [10]. Within the pelvic ring, the pectineal ligament covers the pectineal line of the pubis (Figure 1) [11]. Initial characterization of the pectineal ligament in embalmed cadavers noted the difficulty in identifying the PL from the fascia covering pectineus, but easier to distinguish from the periosteum lacunar ligament [12]. More recent characterization of the ligament in fresh, alcohol-fixed, and Thiel-fixed specimens provided a further description of the PL as a thickening on the linea terminalis, with connection to the superior pubic ligament ventrally, and the supero-posterior pubic symphysis [11]. Like previous reports, the ligament was noted to have an anterior connection with the inguinal ligament via the lacunar ligament [11,12]. Both reports document histological preparations of the PL comprised of dense collagen fibers arranged in parallel bundles [11,12].

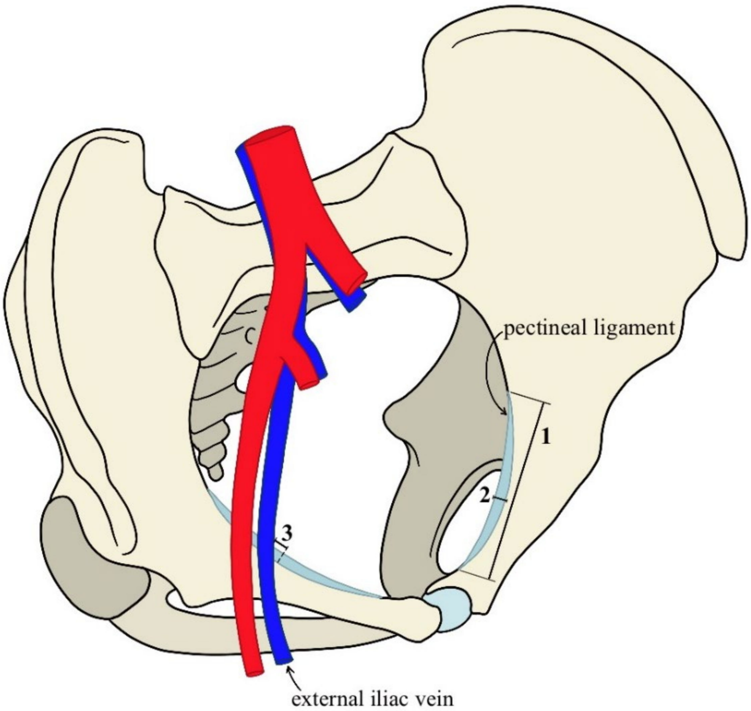

Figure 1. Pectineal ligament measurements. 1. Measured length of the pectineal ligament, 2. measured length of ligament from its midpoint to the external iliac vein, and 3. measured ligament width at its midpoint.

The anatomy of the pectineal ligament is clinically relevant given its position in the pelvic ring as well as its utility in urogynecologic and hernia repair surgeries. In urogynecology, the PL has a historic role in colposuspension, developed by Dr. John Burch, to establish a minimally invasive surgery to treat stress urinary incontinence [13]. Recent reports have reemphasized its role in reducing the risk of injury with a low rate of perioperative complications [13] as well as treating recurrent stress incontinence [14]. The ligament is strong enough to serve as a stabilizer in anterior pelvic ring fractures [15,16]. Indeed, imaging studies evaluating the increasing degree of pelvic fracture severity correlate with ligamentous lesions [16]. A 4–5 mm diameter displacement of the superior pubic ramus always resulted in PL injury as visualized by MRI [16]. The parallel orientation of collagenous fibers [11,12] provides structural stability leading to fewer high-grade ligamentous lesions identified in minimally displaced fractures [16]. Similarly, biomechanical evaluation of PL insufficiency in hemipelves revealed a significant increase in fracture movement [15].

In the laparoscopic pectopexy, the vaginal apex is lifted via mesh fixation to the pectineal ligaments (PL) bilaterally along the superomedial borders of the pubic rami [8]. This mesh follows the natural path of the round ligaments; therefore, the mesh does not cross sensitive structures (e.g., bowel and ureters) or narrow the pelvic cavity [3,5]. In a randomized clinical trial comparing sacrocolpopexy to pectopexy, Noe et al. [5] found that pectopexy has fewer postoperative complications, including defecation disorders, cystoceles, and recurrent prolapse. Other sources indicate that pectopexy is safer and better tolerated in patients with comorbidities such as obesity [3], intolerance to Trendelenburg positioning [17], and in patients with a history of pelvic adhesions or diverticulitis [18].

Cosson et al. [19] found that the pectineal ligament was more durable than other pelvic ligaments when sutured, indicating a potentially lower recurrence rate of prolapse [20]. Although several sources have studied morphology and vascular relationships of the PL [11,19,20], information regarding the biomechanical properties of the PL and SALL is lacking specifically in pelvic organ prolapse repair.

Given the utilization of these ligaments as anchor points in prolapse surgery, the objective of this study was to provide a more thorough characterization of the PL and evaluate the biomechanical properties of the PL and SALL to evaluate the risk of ligament tearing and deformation. These data would be applicable for gaining a better understanding of which procedure uses a more reliable ligament, potentially reducing the recurrent prolapse rate.

2. Material and Methods

2.1. Dissection of Cadaveric Donors

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Institutional Biosafety Committee (#1664206-2). A total of 17 female formalin-embalmed donors were utilized (mean, 77.25 years; range 65–94 years). Inclusion criteria included a female donor, complete anatomy of the pelvic region, a lack of known surgical history in this area, and a normal gross anatomical appearance upon dissection. Exclusion criteria included any male donors, and female donors with surgical history in the pelvic region either reported or noted/suspected upon dissection (donor with unreported hysterectomy). Samples harvested included the PL (right, $n = 17$; left, $n = 16$) and the SALL ($n = 15$).

Ligament collections were performed on donors who previously underwent pelvic hemisection, providing access to the ligaments. The PL samples, located bilaterally along the superomedial borders of the pubic rami, were cleared of fascia and overlying vessels except for the external iliac vessels. Measurements characterizing the PL, as well as measurements of its relationship to the external iliac vein (EIV) were obtained using Mitutoyo Absolute IP-67 digital calipers (Figure 2). To characterize the PL, the overall length of the ligament, from its origin to insertion along the pubic ramus, was determined. To determine the midpoint of the PL, the length of the ligament was divided in half.

The midpoint was subsequently located in situ, and the thickness of the ligament was measured. Finally, the midpoint was used to evaluate the distance of the PL to the EIV. Once known, the midpoint to the EIV was measured. Measurements were recorded into an Excel spreadsheet (Microsoft Office, Microsoft, Redmond, WA, USA).

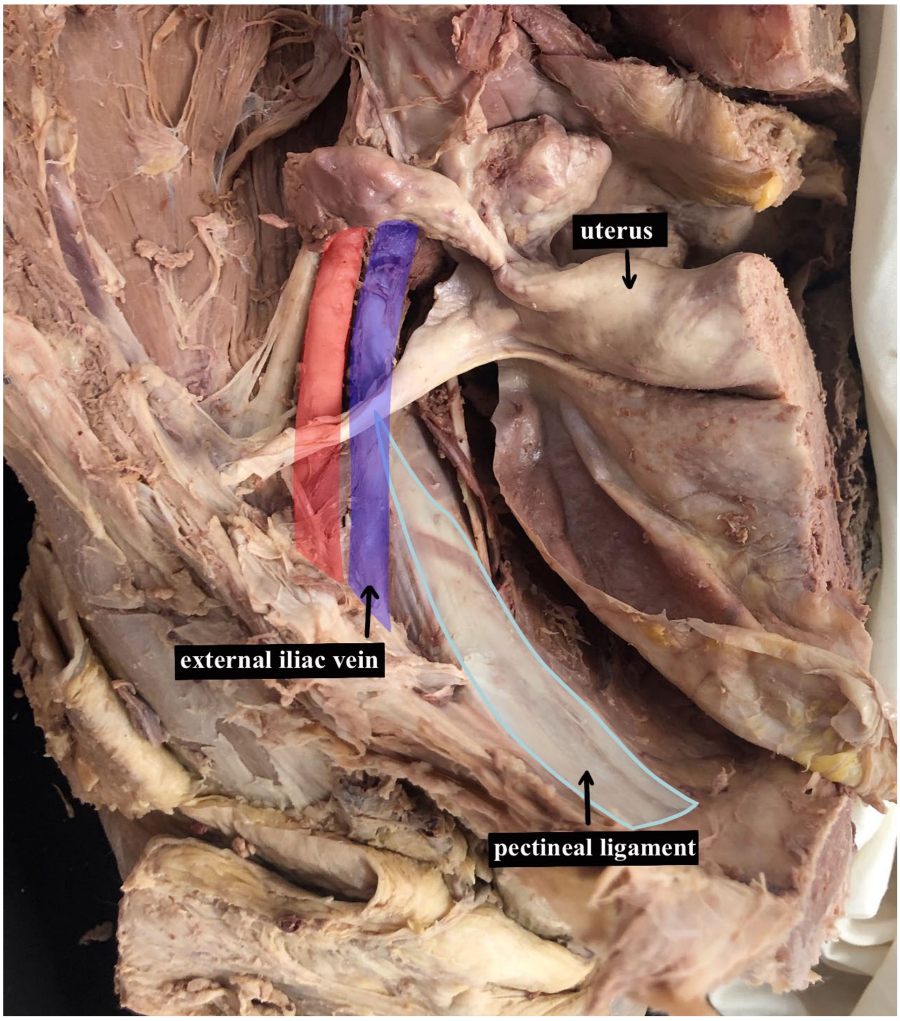

Figure 2. Pectineal ligament dissection in situ. The pectineal ligament is shaded light blue; the external iliac vein is shaded in dark blue; the external iliac artery is shaded in red.

After recording measurements, two transverse scalpel cuts at the proximal and distal ends of the PL (along the superior pubic ramus) were made. The PL was lifted from the pubis using forceps, and a scalpel was used to separate the ligament from the bone. Once free, the PL was cleared of any additional fascia and periosteum. They were stored in sealed containers that contained a wetting solution (proprietary blend).

In addition, the SALL was located on the anterior sacral promontory and cleaned of fascia and overlying vessels using blunt dissection. With a scalpel, two transverse cuts were made between S2 and S3 approximately one to two inches apart. The ligament was reflected from the sacrum to expose the posterior aspect and remove the adhered sacral periosteum. The ligaments were stored in a sealed container with the wetting solution.

2.2. Biomechanical Testing

Following extraction, PL and SALL underwent biomechanical testing (n = 48). Ligaments less than 3 mm in length (n = 3) were excluded. For each ligament, the force at failure, toughness, and elastic modulus were measured using an FLS-1 Mechanical Tester

(Lucas Scientific, Pedasi, Los Santos, Panama), in line with previous measurements reported by Millhuff et al. [21]; each ligament sample was tested at its measured midpoint. The measured peak force at failure in Newtons (N) represents how much force can be applied to a material before failure [22–25]. It has a maximum threshold of 1000 N of peak force at failure. Toughness (R), measured in Joules per cubic meter (Jm^{-2}), measures the energy needed to drive a crack through a given tissue and is indicative of a material's ability to arrest tearing [22–24]. Materials registering higher toughness values require more energy to produce catastrophic failure. Elastic (Young's) modulus (E) represents the degree of deformation (in megapascal pressure unit, Mpa) a material can withstand relative to the force or stress placed upon it [22–25]; a higher elastic modulus denotes the ability of a tissue to withstand higher forces and resist tissue deformation [21].

2.3. Statistical Analysis

All statistical analyses were completed using SPSS version 26 (IBM, Armonk, NY, USA). The significance for all tests was set at $p = 0.05$. Descriptive statistics were calculated for the measurement data for the PL and SALL. To evaluate any differences in laterality of the right and left PL an independent *t*-test was used. Given the surgical utilization of the right and left PL independently in the pelvic cavity with pectopexy, right and left PL samples were statistically evaluated as independent mean values and as a combined mean value to compare to the SALL. This allows for analysis of any differences in the ligament function as independent anchor points as well as a collective anchor point to be evaluated. Differences in material properties of the PL (right, left, combined) and SALL were evaluated using an independent *t*-test or Mann–Whitney U test based on data distribution.

3. Results

3.1. Characterization of the Pectineal Ligament

The mean pectineal ligament lengths are recorded in Table 1. No significant differences ($p = 0.05$) were identified between the right and left pectineal ligaments for any of the measurements recorded (length, midpoint to EIV, width at midpoint). The SALL was notably thinner upon visual inspection. Measurement of the ligament thickness was impacted due to frequent tearing of the sample during dissection, and the thickness was not recorded.

Table 1. Characterization of the pectineal ligament.

	Measurement	**Mean Length ± SD (mm)**	**Min (mm)**	**Max (mm)**
Right PL	Length	66.35 ± 12.02	43.79	85.54
	Midpoint to EIV	16.79 ± 8.82	4.24	32.36
	Width at midpoint	6.83 ± 1.17	4.81	8.94
Left PL	Length	65.58 ± 11.32	41.52	85.31
	Midpoint to EIV	14.42 ± 7.86	3.14	27.94
	Width at midpoint	6.64 ± 0.98	4.62	8.17

Mean values ± standard deviation (SD); PL, pectineal ligament (right, $n = 17$; left, n-16); EIV, external iliac vein.

3.2. Biomechanical Properties of the Pectial and Sacral Anterior Longitudinal Ligaments

The biomechanical properties testing results of the PL and SALL are included in Table 2. No significant differences were identified in the peak force at failure ($p = 0.79$), toughness ($p = 0.58$), or elastic modulus/stiffness ($p = 0.40$) when comparing samples of the right and left PL, suggesting these ligaments have comparable material properties irrespective of side. When these properties were compared to the SALL, individual PL samples (right and left) had significantly greater peak force at failure (right, $p = 0.001$; left, $p = 0.004$) and toughness (right, $p = 0.004$; left, $p = 0.005$). Each right and left PL also had a larger average elastic modulus than the SALL, but these values did not approach significance (right, $p = 0.290$; left, $p = 0.143$).

Table 2. Biomechanical properties of the pectineal and sacral anterior longitudinal ligaments.

Ligament	Peak Force at Failure (N)	Toughness (Jm^{-2})	Elastic Modulus/Stiffness (MPa)
Right PL	80.54 ± 22.89	5778.17 ± 2023.38	411.89 ± 277.69
Left PL	83.23 ± 34.76	6243.56 ± 2746.07	543.94 ± 571.33
Combined PL	80.88 ± 24.97	5961.61 ± 2022.31	486.19 ± 357.72
SALL	53.55 ± 19.44	3847.93 ± 1319.69	323.97 ± 242.42

Mean values ± standard deviation (SD); PL, pectineal ligament (right, n = 17; left, n-16); SALL (n = 15), sacral anterior longitudinal ligament (SALL); combined PL denotes mean values of right and left measurements for the PL.

Additionally, when a combined value (right and left) for the PL was compared to the SALL, the combined PL values also resulted in statistically significant increased peak force at failure (p = 0.005) and toughness (p = 0.002). For elastic modulus, the mean combined PL value was larger than SALL but did not approach significance (p = 0.110) (Table 3).

Table 3. Statistical comparisons of material properties of the pectineal ligament and sacral anterior longitudinal ligament.

Measurement	Right PL vs. SALL	Left PL vs. SALL	Combined PL vs. SALL
Peak Force at Failure (N)	0.001	0.004	0.005
Toughness (Jm^{-2})	0.004	0.005	0.002
Elastic Modulus/Stiffness (MPa)	0.290	0.143	0.110

For combined analysis, mean values of right and left measurements were utilized as a single ligament measurement. An independent t-test was completed for all toughness comparisons and for the right PL vs. SALL values. A Mann–Whitney U analysis was completed for all modulus comparisons and for both the left PL and combined PL vs. SALL values. p = 0.05 for all analyses.

4. Discussion

The pectineal ligament and anterior longitudinal sacral ligament have important clinical relevance in urogynecologic surgery and are each used in a range of procedures. The pectineal ligament is referred to in the literature as robust [11,12] and found to be significantly stronger than the sacrospinous ligament and arcus tendineus of the pelvic fascia [19]. Indeed, the characterization of the gross appearance and length of the pectineal ligament [11,20], as well as its distance to the external iliac vein [20] was congruent yet had notable differences as compared to previous reports [12]. Indeed, the mean length for the right and left PL samples (66.35 ± 12.02 mm and 65.58 ± 11.32 mm, respectively) was increased as compared to a single, combined group mean of 53 mm [12]. Additionally, the width at the midpoint for the PL (6.83 ± 1.17 mm and 6.64 ± 0.98 mm) was also increased as compared to the 2.6 mm reported by Faure and colleagues [12]. This difference is largely due to the experimental approach in each of the reports; Faure and colleagues grossly identified the thickest region of ht PL and measured its thickness. In comparison, this study took a more consistent approach and measured the thickness at the midpoint of the PL, rather than using gross approximation of the thickest PL region.

Additionally, evaluation of the PL in fresh, cadaveric donors has been bilaterally characterized [20]. The data reported herein are consistent with the values in embalmed, female donors for both the total length of the pectineal ligament, left- and right-sided samples (L, 59 ± 7.6 mm; R, 65 ± 11.4 mm), as well as the midpoint to the EIV (L, 10.4 ± 2.3 mm; R, 12.5 ± 4.3 mm). Our data for the midpoint to the EIV was slightly larger, measuring 14.42 ± 7.86 mm (left) and 16.79 ± 8.82 mm (right), respectively. A key difference in our study was the lack of measurements to the right and left corona mortis as well as the distance to each obturator canal. Future evaluation of these distances in embalmed donors would likely be consistent with measurements obtained for fresh donors [20] (patulogua).

The biomechanical properties of the PL and SALL have not been characterized and previous reports characterizing the PL have called for such evaluation to be completed [11]

(Steinke). Our novel comparison revealed that the PL material properties performed significantly better under tension than the SALL, which was accurate irrespective of the PL evaluated independently based on sidedness (right PL vs. SALL; left PL vs. SALL) or as combined (mean right, left PL) value (Table 3). Data indicate a higher value for peak force at failure for the PL, and the PL had statistically higher values for toughness (Table 3), or the material's ability to resist a tear once begun. Collectively, this suggests that the PL may resist recurrent prolapse longer than the SALL, potentially making it a more reliable long-term solution for patients with pelvic organ prolapse.

For elastic modulus, the results indicate increased values of stiffness of the PL as compared to the SALL, although the difference was not statistically significant when evaluated independently or as a combined value. This property was important to characterize, as it has not been reported previously for the PL.

The PL and SALL have distinct utility in urogynecologic surgery. The PL extends over the iliopectineal line along the superomedial border of the pubic bone [12,20] and is commonly used in pelvic organ prolapse repair. Additionally, it often serves as an anchor point in hernia repair, procedures to correct urinary incontinence, orthopedic/trauma surgery, and neovaginal reconstruction [11,15,16]. The higher values for toughness and elastic modulus of the PL reported herein suggest these factors may positively impact the success and longevity of the pectopexy in pelvic prolapse correction.

Statistical analysis of the biomechanical properties of single PL samples is of key importance specific to recent approaches utilizing unilateral pectineal attachment. Select reports have documented a unilateral, single-site pectopexy, which offers a simplified surgical approach, decreased surgical time, and does not require bowel manipulation [10,26]. The unilateral approach provides medial, tension-free positioning of the uterus, stable results, and normal pelvic floor mobility [26]. Our data complement the unilateral surgical option by providing contextual detail as to the biomechanical properties of each right and left pectineal ligament versus referencing combined properties as a single sample. Interestingly, biomechanical testing of suture and anchor methods in pectopexy has provided additional evaluation of the PL properties as a fixation site [27,28]; there was no significant difference in the ultimate load, stiffness, or failure for the mesh plus simplified, single 'interrupted' suture as compared to mesh with continuous suture [27] and the PL lacked statistically significant differences in the average extraction force needed to induce expulsion of the anchoring system or non-absorbable sutures from the ligament [28].

The SALL is used in the sacrocolpopexy procedure, the standard for apical pelvic organ prolapse repair. This approach lifts the vaginal apex via mesh fixation to the SALL [3], but unfortunately has a high recurrence rate [6,7], typically attributed to mesh complications [3,6,29,30]. Current explanations for recurrent prolapse are individual anatomical variations, age, and inherent connective tissue laxity [2,6]. A single case report has detailed recurrent prolapse due to possible structural concern with the anterior longitudinal sacral ligament [4]. Interestingly, the thinness of the anterior longitudinal ligament has been noted by surgeons during sacrocolpopexy procedures as a relative weakness and enhanced risk of periostitis if the sacrum is accidentally punctured [5]. Indeed, our observations, albeit anecdotal, in attempting to harvest this ligament during dissections were hampered as the samples were not robust for analysis. The decreased biomechanical strength specific to the toughness and elastic modulus of the anterior longitudinal sacral ligament as compared to the pectineal ligament reported herein possibly explains the increased rate of prolapse recurrence after sacrocolpopexy. Evaluation of the biomechanical properties of the pectineal and anterior longitudinal sacral ligaments isolated from prolapse repair surgeries would provide a better understanding of the biomechanics of these ligaments and how they handle the stresses placed upon them during prolapse repair.

While this study utilized cadaveric tissues for measuring ligament toughness and elastic modulus, the biomechanical property measurements are analogous to living tissue given that dense connective tissue with low vascularization is less saturated with embalming fluid than other tissues. Furthermore, previous reports have characterized the structure and properties of embalmed human tissues [31] and have not reported significant differences that warrant disregard of data. In contrast, cyclic biomechanical analysis of the PL in fresh and embalmed cadavers noted decreased cycles to reach functional stability in a single, female donor at 14.5 cycles of load exposure, which is statistically decreased as compared to fresh donors (19.1 cycles), but no overall system failure occurred [32]. One caveat of this comparison is the measurements were collected from intact pelves as compared to our dissected samples. Finally, while the FLS-1 Mechanical Tester is not widely used for the measurement of human biological materials, it is adequate for such measurements and has been utilized in the characterization of vertebral ligaments [21].

Limitations

This study is not without limitations. The measurements in this study were collected from formalin-embalmed Caucasian donors with a mean age of ABC years. Additionally, there would be a benefit in evaluating the increased number of female donors; however, this is complicated by a few different factors: (1) the overall number of individuals opting into body donation for medical education and research, (2) the number of female donors within a given donor population, and (3) the number of female donors that have complete genitourinary anatomy due to hysterectomy or other surgical interventions. The limited sample would benefit from the evaluation of increased size and inclusion of male specimens to better represent a wider varied group of patients and applicability to procedures beyond pectopexy, including hernia repair and anterior pelvic fractures. Finally, it would be of great interest to provide an evaluation of the biomechanical properties of formalin-fixed, Thiel-embalmed (soft embalming), and fresh frozen samples to better appreciate any differences in tissue behavior relative to apical pelvic organ prolapse repair.

5. Conclusions

In conclusion, the pectineal ligament withstands stresses (i.e., higher peak force at failure) better than the sacral anterior longitudinal ligament. It was also better able to withstand crack propagation as indicated by the higher toughness values. To the best of our knowledge, this is the first study to investigate and compare these biomechanical properties between the anchoring ligaments used for apical pelvic organ prolapse. Although the pectopexy currently does not replace the sacrocolpopexy as the standard prolapse procedure, surgeons would benefit from increased awareness of the biomechanical properties inherent among the two anchoring ligaments. These data provide a deeper understanding of the biomechanical properties of the pectineal ligament and demonstrate its inherent ability to better withstand stress with increased toughness. The usage of the PL as a bilateral or unilateral anchor point in pectopexy procedures uses a more reliable ligament than the SALL, and its surgical utility may result in reduced recurrent prolapse rates.

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Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki, and approved (10/21/2021) by the Institutional Biosafety Committee of Kansas City University (#1664206-1).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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