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Article

The Relationship Between Superficial Lower Leg Length and Plantaris Tendon Length for Tendon Graft Availability: An Anatomical Morphometric Study in Cadavers

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Abstract

Background: The Plantaris tendon is a viable option for tendon grafting in various reconstructive procedures. This study aimed to develop a predictive model estimating plantaris tendon length (PTL) based on lower leg length (LL) to provide a preoperative baseline reference. Methods: An investigation was conducted on 238 lower limb sides from Thai cadavers to determine the prevalence and morphometry of the plantaris muscle. Measurements included PTL, tendon width (PTW), muscle belly length (PBL), total muscle length (PML), and LL. Results: The plantaris muscle was present in 88.24% of lower limb sides. A significant correlation was observed between PTL and LL ($r = 0.581$, $p < 0.001$). The predictive equation established was: PTL (mm) = 79.167 + [0.574 × LL (mm)], with a standard error of estimate of 20.06 mm. Testing on a separate sample showed no significant difference between predicted and actual PTL values ($p = 0.206$). Out of the 179 sides measured, 64.80% met the criteria for tendon graft suitability. Conclusions: These findings indicate that LL serves as a practical surface measurement providing an approximate preoperative estimate of PTL in a Thai population. Due to its moderate predictive power, it should be used as a supplementary assessment rather than a sole planning tool for surgical applications.

Keywords: plantaris; lower leg length; predictive model; tendon graft; reconstructive surgery; cadaver; anatomy

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1. Introduction

The plantaris muscle (PM) is a fusiform muscle that, together with the gastrocnemius and soleus, is collectively referred to as the triceps surae muscle [1]. Those muscles are innervated by the tibial nerve (S1, S2). The PM is absent in 7–20% of limbs [1]. It varies in size (7–13 cm) and shape [1,2]. It proximally attaches to the lateral supracondylar line of the femur and the oblique popliteal ligament, running down the popliteal fossa. It lies between the popliteus and the lateral head of the gastrocnemius. Its tendinous portion can be palpated along the medial aspect of the Achilles tendon into its calcaneal insertion [1,3].

PM has been considered to be an organ of proprioceptive function for the larger, more powerful plantar flexors [1]. PM and its associated tendon have been an academic interest due to their advantages as a viable option for tendon grafts [4–6]. Despite the availability of various tendon choices for grafting, including the palmaris longus, flexor digitorum superficialis, and extensor digitorum longus [7], the nonessential nature of

PM in comparison to other options is notable. Additionally, PM exhibits outstanding characteristics such as high prevalence, considerable length, and minimal side effects post-excision [7]. To prioritize minimizing invasive procedures, many studies have been conducted about the correlation between leg length and Plantaris tendon length (PTL) [8]. According to Milone et al. [9], not only leg length but also lower leg length (LL) showed a correlation with Plantaris tendon (PT).

Currently, the PT is utilized in various reconstructive surgeries, such as hand tendon reconstruction in sports trauma [5], atrioventricular valve repair [10], and ankle ligament reconstruction [11]. Moreover, PT was also used in the interventions that aimed for strengthening multiple structures, such as those of the Achilles tendon and lateral ankle ligaments, rotator cuff ligament, and anterior cruciate ligament [12,13]. Therefore, the characteristics and prevalence of PM were systematically investigated to evaluate its benefits in various aspects. The study by Jakubietz et al. [14] showed the advantages of PT over the palmaris tendon for grafting, highlighting its higher prevalence and greater length compared to the palmaris longus muscle. Furthermore, the suitability of PT for reconstructive procedures [15] and the relationship of ethnicity to its availability, including Caucasian, Indian, Japanese, Chinese, African, Brazilian, and Korean populations [7,16,17], were studied. However, those studies in a Thai population were not examined comprehensively.

Therefore, in this study we measured (1) the maximum Plantaris tendon length (PTL) (2) the Plantaris tendon width (PTW), (3) the maximum Plantaris muscle length (PML), (4) the maximum Plantaris muscle belly length (PBL) and (5) the lower leg length (LL) to study the prevalence and morphological characteristics; as well as estimating the length of plantaris tendon by using the lower leg length, according to the study of Milone et al. [9], for graft donor in trauma reconstruction in a Thai population.

2. Materials and Methods

This descriptive study was performed at the Department of Anatomy, Faculty of Medicine, Chiang Mai University, and was approved by the Research Ethics Committee of the Faculty of Medicine, Chiang Mai University (Exemption No. 0164/2024). The cadavers at the Department of Anatomy, Faculty of Medicine, Chiang Mai University consist of individuals who legally donated their bodies to the Department of Anatomy for academic and research purposes. Detailed records, including age at death, sex, cause of death, and domicile, are maintained in the department's database.

At the time of this study, 134 embalmed cadavers of Thai individuals (88 males and 46 females), ranging in age from 28 to 94 years with an average age of 68.19 years (±13.99 SD), were dissected by medical and paramedic students under the supervision of a faculty anatomy instructor, with both lower legs examined in the prone position. All cadavers with intact calf regions and showing no signs of previous trauma, surgery, or deformities were included. Those with damaged or missing lower limbs (from the mid-thigh to the foot) or an absent plantaris muscle and tendon were excluded from this study. The plantaris muscle (PM) and tendon (PT) were identified on 179 sides of the lower limb and subsequently harvested for the measurement. The myotendinous junction was macroscopically identified at the transition where the dull, reddish-brown muscle fibers ended and the shiny tendinous tissue began. Five measurements were taken using a digital caliper to the nearest 0.01 mm, as described in Table 1 and illustrated in Figure 1.

Table 1. Definitions of the measurements.

Measurements	Definitions
Maximum plantaris tendon length (PTL) *	Maximum distance between the myotendinous junction of the plantaris muscle and its fusion point with the calcaneal tendon
Plantaris tendon width (PTW) *	Maximum width of plantaris tendon measured at the midpoint of plantaris tendon [8]
Maximum plantaris muscle belly length (PBL) *	Maximum distance of plantaris muscle belly while extended, from the point of origin to the myotendinous junction of plantaris muscle [8]
Maximum plantaris muscle length (PML)	Length calculated by combining PBL and PTL [8]
Lower leg length (LL) †	Length measured between head of fibular and tip of lateral malleolus [9]

* Measure using a digital caliper (Mitutoyo Corporation, Kawasaki, Japan). † Measure using a measuring tape (Shinwa Measuring Tools Corporation, Sanjo, Japan).

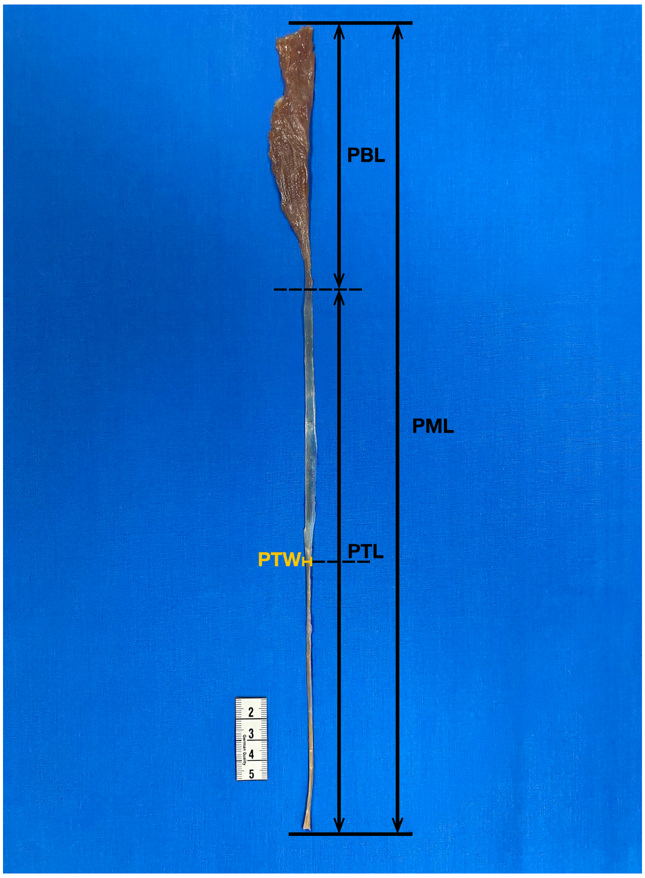

Figure 1. Plantaris muscle and tendon measurements as described in Table 1.

IBM SPSS Statistics 26.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analyses, with the level of significance set at $\alpha = 0.01$. This threshold was chosen to control the error rate across multiple exploratory morphometric comparisons within the same dataset. The Kolmogorov-Smirnov test was used to evaluate the normality of the data, and the descriptive statistics were obtained. Based on the normality testing, normally distributed variables (PTW, PBL, and LL; $p > 0.01$) were analyzed using parametric tests, whereas non-normally distributed variables (PTL, PML, and the PTL/LL ratio; $p < 0.01$) were analyzed using non-parametric tests. To assess observer reliability, a minimum subsample of 30 individuals is recommended [18]. Accordingly, intra- and inter-observer reliability for all variables was evaluated by re-measuring 34 randomly selected lower-limb sides on two occasions separated by two days. For each variable, each observer performed three consecutive measurements, and the mean value was used for subsequent analysis. The reliability was assessed using intraclass correlation coefficients (ICC). The difference between left and right measurements was inspected. The ratio of the maximum plantaris tendon length (PTL) to the lower leg length (LL) was also calculated to examine the difference between males and females. The suitability of the plantaris tendon for tendon grafting was classified according to the study of Harvey FJ et al. [19]. The relationship between PTL and LL was examined, and a predictive model for PTL was established using simple linear regression. For the linear regression analysis, the normality, linearity, and homoscedasticity of the residuals were checked and confirmed using residual plots and normal probability (P-P) plots to ensure the validity of the model. The accuracy of the predictive model was then tested in a separate sample of 29 lower limb sides. The flowchart of the allocation of the samples utilized in this study is shown in Figure 2.

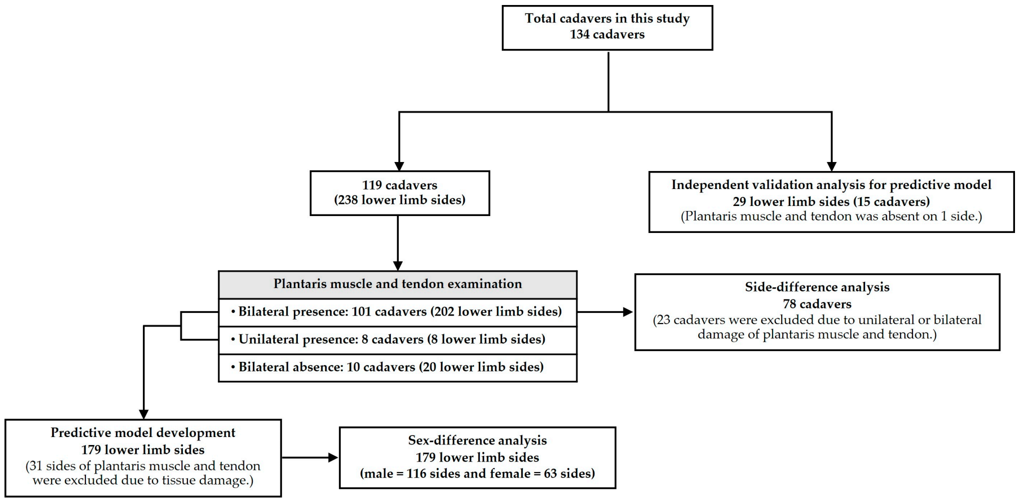

Figure 2. Flowchart illustrating the allocation of the samples for analyses in this study.

3. Results

3.1. Study Population and Sample Flow

A total of 134 cadavers were utilized in this study and allocated into two separate groups (Figure 2). The predictive model was developed using a sample of 119 cadavers (238 lower limb sides). Within this group, the plantaris muscle and tendon were bilaterally absent in 10 cadavers (20 sides), and 31 sides were excluded due to local tissue damage, resulting in a final analytical sample of 179 sides for the morphometric and regression analyses. For the side-difference analysis, a subset of 78 cadavers from this group was used, excluding individuals with unilateral or bilateral tissue damage to ensure accurate paired comparisons. The validation analysis was performed on a completely separate cohort consisting of the remaining 15 cadavers (29 lower limb sides, as the muscle was absent on 1 side), ensuring that the validation data were entirely independent of the model development sample.

3.2. Assessment of Observer Reliability

Table 2 presents the intraclass correlation coefficients for all variables, with all estimates achieving statistical significance ($p < 0.01$). Both intra- and inter-observer reliabilities demonstrated excellent to good reproducibility for LL, PBL, PML, and PTL. Conversely, PTW exhibited moderate reliability. Overall, the measurement protocol in this study showed stable and acceptable reproducibility across all parameters.

Table 2. Intra- and inter-observer reliability for the measurements.

Measurements (n = 34)	Intraclass Correlation Coefficient (95% Confidence Interval)	
	Intra-Observer *	Inter-Observer *
PTL	0.816 (0.663, 0.904)	0.833 (0.692, 0.913)
PTW	0.629 (0.377, 0.795)	0.663 (0.424, 0.816)
PBL	0.957 (0.916, 0.978)	0.926 (0.858, 0.962)
PML	0.834 (0.692, 0.913)	0.855 (0.729, 0.925)
LL	0.987 (0.975, 0.994)	0.948 (0.899, 0.974)

* Both intra-observer and inter-observer reliabilities were conducted using a two-way mixed-effects model with absolute agreement (single measures) with a significance level of 0.01.

3.3. Assessment of Side Differences

In this study, dissections were performed on 119 cadavers, all of which had intact lower legs on both sides. The plantaris muscle was observed in both the left and right legs of 101 cadavers (84.87%). However, in 8 cadavers (6.72%), the plantaris muscle was present in only one leg, while in 10 cadavers (8.40%), the muscle was absent on both sides. Only cadavers with intact plantaris muscles and tendons on both sides were included in the assessment of side differences. No statistically significant differences were shown between the left and right sides across all measurements (Table 3).

Table 3. Side-difference test for the measurements.

Measurements	Side Difference	
	N	p Value
PTL ‡	78	0.101 ‡
PTW *	78	0.906 *
PBL *	78	0.552 *
PML ‡	78	0.018 ‡
LL *	78	0.578 *

‡ Statistical analysis was conducted using the Wilcoxon signed-rank test with a significance level of 0.01. * Statistical analysis was conducted using a paired sample t-test with a significance level of 0.01.

3.4. Assessment of Sexual Differences

Statistically significant differences were found between males and females in PTL, PBL, PML, and LL measurements ($p < 0.01$), with males exhibiting larger values than females (Table 4). In contrast, PTW and the PTL/LL ratio showed no significant differences between sexes ($p > 0.01$). Descriptive statistics for all measurements, including the minimum, maximum, mean, and standard deviation, are also presented in Table 4.

Table 4. Descriptive statistics for the measurements and sex-difference test between males and females.

Measurements (mm)	Male (N = 116)				Female (N = 63)				Sex Difference
	Min	Max	Mean	SD	Min	Max	Mean	SD	p Value
PTL †	160.25	437.87	293.54	31.77	160.44	341.42	275.55	31.74	0.000 *
PTW ˆ	0.96	8.52	3.09	1.17	1.11	5.94	2.82	1.06	0.125
PBL ˆ	60.08	160.53	109.07	17.02	54.26	184.84	99.58	24.18	0.007 *
PML †	281.66	531.40	402.62	33.80	218.52	445.12	382.03	69.32	0.000 *
LL ˆ	318.00	439.00	371.91	24.64	313.00	402.00	350.21	20.78	0.000 *
Ratio of PTL to LL †	0.43	1.06	0.79	0.07	0.46	0.97	0.79	0.08	0.849

† Statistical analysis was conducted using a Mann-Whitney U test with a significance level of 0.01. ˆ Statistical analysis was conducted using an independent samples t-test with a significance level of 0.01. * Significant difference between sexes (p-value < 0.01).

3.5. Plantaris Tendon Length (PTL) Prediction Using Lower Leg Length (LL)

Table 5 presents the univariate linear regression analysis for predicting PTL using LL. The results indicate a significant positive correlation between PTL and LL (standardized coefficient = 0.581, $p < 0.01$). The regression model explains 33.4% of the variance in PTL, with a standard error of estimate (SEest) of 20.06 mm. The derived regression equation is: PTL (mm) = 79.167 + [0.574 × LL (mm)].

Table 5. Univariate linear regression analysis for plantaris tendon length (PTL) prediction using lower leg length (LL).

Variable	Unstandardized Coefficient		95% CI for β	Standardized Coefficient	t	*p* Value
	β	Std. Error		β		
(Constant)	79.167	22.565	(34.620, 123.713)		3.508	0.001 *
LL	0.574	0.062	(0.452, 0.696)	0.581	9.288	0.000 *
$SE_{est} = \pm 20.06$ $R^2 = 0.338$; Adjusted $R^2 = 0.334$; F = 86.262						

* Statistical analysis was conducted using enter-method linear regression with a significance level of 0.01.

To assess the accuracy of the model, it was tested on a separate sample of 29 lower limb sides. Model performance was evaluated using a mean absolute error (MAE) of 13.02 mm and a root mean square error (RMSE) of 15.63 mm. The mean difference between the predicted and actual PTL of 29 lower limb sides, indicating systemic prediction bias, was −2.05 mm. A Bland–Altman analysis revealed 95% limits of agreement ranging from −32.96 mm to +28.86 mm. Moreover, the correlation between the predicted PTL and actual PTL in the separate sample was moderate (Spearman's correlation = 0.517, $p = 0.004$). The Wilcoxon signed-rank test ($p = 0.206$) indicated no significant difference between predicted and actual PTL values, suggesting that the model provides a moderate but statistically significant capability for estimating PTL based on LL.

3.6. Suitability of Plantaris Tendon for Tendon Grafting

The recommended criteria for determining tendon graft suitability, as proposed by Harvey et al. [19], were applied to the results of this study. Of the 179 sides measured, 116 sides (64.8%) met the criteria, while 63 sides (35.2%) did not qualify (Table 6).

Table 6. Distribution and proportion of plantaris tendon suitability for grafting.

Criteria	Amount (Sides)	Percentage (%)
PTL ≥ 30 cm with PTW ≥ 1.5 mm *	83	46.4
PTL ≥ 15 cm with PTW ≥ 3.0 mm *	59	33.0
At least one criterion met	116	64.8

* Criteria of tendon graft suitability proposed by Harvey et al. [19].

4. Discussion

The plantaris muscle and its tendon have garnered significant academic interest due to their potential as reliable sources for tendon grafts [4–6]. Among various tendon options for grafting, such as the palmaris longus, flexor digitorum superficialis, and extensor digitorum longus [7], the plantaris tendon stands out for its nonessential role, high prevalence, substantial length, and minimal complications post-excision [7,20]. This study contributes to understanding the plantaris tendon by providing data on its prevalence and morphological characteristics within a Thai population as well as its suitability for tendon grafting. In addition, the relationship between plantaris tendon length and lower leg length will be estimated to support that lower leg length is a reliable parameter for estimating the length of the plantaris tendon in surgical planning.

From the 238 sides of the lower limb, the prevalence of the plantaris muscle and tendon in this study was 88.24%. Additionally, the bilateral prevalence in this study was 84.87%, which is slightly lower than the study of Shiva et al. [20] reporting 88.80%. Some of these differences in prevalence may be attributed to the sample size, as well as population and ethnic variations reported in the previous study [7]. Despite the inconsistent prevalence and anatomical variability in plantaris tendon insertion sites [7,8], the observer variability assessments revealed good-to-excellent reproducibility for the majority of measurements. Although PTW exhibited moderate reliability, the overall findings confirm that the designated anatomical landmarks provide a stable framework for practical application. Lower leg length was selected as the reference parameter because it encompasses the anatomical region of interest and includes clearly defined anatomical landmarks—the head of the fibula and the lateral malleolus—[9] that can facilitate precise measurements. Regardless of the difference in measurement methodology compared to the previous studies that used total leg length [8], the present study remains significant in its contribution to the anatomical understanding of the plantaris tendon.

In addition, this study observed no significant differences between left and right-side measurements. These findings align with the previous studies [7,8] that reported no side differences in PTL and PTW, suggesting that either side can be used interchangeably for reconstructive procedures. Anatomical variations in muscle presence or absence on one or both sides were also noted in previous literature [7,20–22] as well as in the present study, emphasizing the need for medical imaging technologies such as sonography to help guide the tendon availability before surgery.

In this study, sexual differences were evident in PTL, PBL, PML, and LL measurements, with males exhibiting larger values than females. These results are consistent with a previous study [8] and may be attributed to hormonal influences, such as testosterone and insulin-like growth factor-1 (IGF-1), which are known to promote increased muscle mass and bone growth. However, no sexual differences were observed in PTW or the PTL/LL ratio, indicating that while the absolute dimensions of the plantaris muscle and tendon vary between sexes, their proportional dimensions remain consistent. These results align with previous findings establishing that sex-based structural differences are often less pronounced in the lower limb musculature than in the upper body [8,23]. This study suggests that the plantaris tendon may be anatomically suitable for sex-mismatched transplantation, where donor-recipient size matching is necessary.

To further evaluate whether biological sex acts as an independent modifier of the relationship between PTL and LL, a multivariable linear regression analysis was additionally performed. When sex and LL were entered simultaneously into the model, LL remained a highly significant independent predictor ($p < 0.001$), whereas sex was found to be statistically non-significant ($p = 0.662$) and failed to improve the model's explanatory power (with the adjusted R^2 shifting from 0.334 to 0.331). This statistical redundancy confirms that a simplified, single-variable predictive model is optimal, ensuring ease of use and practical application in preoperative surgical planning without losing predictive accuracy.

Therefore, the single-variable relationship between these two primary variables was examined to facilitate the clinical utilization of superficial lower leg length (LL) for preoperative assessment of plantaris tendon length (PTL). The results demonstrated a significant correlation between PTL and LL ($r = 0.581$, $p < 0.001$), which is comparable to the study by Milone et al. [9], which reported a correlation of 0.60 ($p < 0.05$) between surface fibular length and plantaris tendon length. Although Park et al. [8] reported a higher correlation between PTL and total leg length ($r = 0.721$, $p < 0.001$), the present study focuses on lower leg length as a reference parameter due to its better representation of the superficial anatomical region of the plantaris muscle and tendon. We established a univariate linear regression equation to estimate plantaris tendon length (PTL, mm) based on the lower leg length (LL, mm): PTL = 79.167 + (0.574 × LL). This model accounted for 33.40% of the variance in PTL (adjusted R^2 = 0.334), with a standard error of estimate (SEest) of 20.06 mm. Although a previous study reported higher explanatory power when using height and total leg length to predict PTL (39.20% and 52.00%, respectively) [8], our study advances this framework by being the first to validate the predictive model using an independent, separate cadaveric sample, which was a critical step missing in prior studies [8,9]. The accuracy analyses of the model demonstrated a low overall estimation error (MAE = 13.02 mm; RMSE = 15.63 mm) and a minimal systemic bias of -2.05 mm. However, the 95% limits of agreement spanned from −32.96 mm to +28.86 mm, highlighting that substantial individual variability exists even in the absence of a statistically significant difference between the predicted and actual group means. Although the predictive model in this study provides a reasonable supplementary estimate of PTL based on LL, its limited explanatory power, which leaves approximately two-thirds of the structural variance unexplained, means it should be interpreted with caution in surgical planning. However, ethnicity may influence anatomical relationships, and population-specific differences could affect the relationship between LL and PTL [7]. Therefore, further studies should be conducted in diverse populations to refine and compare predictive models of PTL based on LL across ethnic groups.

Approximately 64.80% of tendons harvested met suitability criteria for grafting based on established guidelines of Harvey et al. [19] (Table 6). Compared to the studies using those guidelines, our study is consistent with findings from studies on Caucasian populations [14], which found a plantaris tendon graft suitability rate of 66.70%, while lower than that of Korean populations [8], which reported 89.00%. These findings clearly highlight the importance of considering population-specific variations when evaluating plantaris tendon graft availability. Consequently, the predictive model in this study provides the first validated baseline metrics specifically for a Thai cohort.

5. Limitations

This study has several limitations. First, the cadavers utilized were embalmed by formaldehyde fixation, which may affect structures such as the joints, muscles, and connective tissues like tendons, potentially influencing the measurements. Future studies using fresh or soft-preserved cadavers would provide more accurate outcomes for tendon graft surgery. Additionally, while the univariate regression model provided a reasonable estimation of PTL based on LL, it explained only about one-third of the total variability. Therefore, the proposed model should be interpreted with caution when applied to standalone surgical planning. Moreover, incorporating other anatomical or demographic factors, such as height or overall limb dimensions, into a multivariable regression model could enhance predictive power and accuracy, given that biological sex was already shown to be a non-significant predictor in this study.

Furthermore, the relatively small validation sample may limit the external validity and generalizability of the established predictive equation. Because of this small sample size, the reported prediction bias and limits of agreement should be interpreted as a preliminary indicator of individual structural variance rather than definitive proof of absolute clinical accuracy. Finally, all specimens in this study were derived from a Thai population, meaning the proposed predictive model may not be directly applicable to other populations with different ethnic characteristics. Therefore, further studies should directly investigate different populations, as well as the surgical harvesting sites, techniques, and accessibility of the plantaris tendon to fully confirm the clinical applicability and practical utility of the proposed equation.

6. Conclusions

This study presents a predictive model for estimating plantaris tendon length based on superficial lower leg length in a Thai population. The findings highlight the utility of a practical surface anatomical landmark that may provide a population-specific approach and preliminary preoperative estimate for tendon graft availability. However, given the moderate explanatory power of the model, it should be utilized as a supplementary reference rather than a standalone tool for surgical planning.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to ethical and privacy restrictions related to the use of human cadaveric donors.

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Conflicts of Interest: The authors declare no conflicts of interest.

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