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AN INVESTIGATION OF THE RELATIONSHIP BETWEEN MUSCLE AND TENDON ARCHITECTURE AND THEIR MECHANICAL PROPERTIES

KAS VE TENDON MİMARİSİ İLE MEKANİK ÖZELLİKLERİ ARASINDAKİ İLİŞKİNİN İNCELENMESİ

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ABSTRACT

Objective: This study aimed to investigate the effects of the architectural features of the gastrocnemius muscle-namely fascicle length, pennation angle, and muscle thickness-and Achilles tendon thickness on the mechanical properties (elasticity, stiffness, and tone) of both the gastrocnemius muscle and the Achilles tendon.

Method: Sixty-three healthy female volunteers aged 18-27 years without musculoskeletal symptoms participated in the study. The pennation angle, thickness, and fascicle length of the gastrocnemius muscle and the thickness of the Achilles tendon were measured using an ultrasonography device with a linear probe (5-12 MHz) (MicrUs EXT-1H, Telemed Ultrasound Medical Systems, Vilnius, Lithuania). A portable myotonometer (MyotonPRO, Myoton Ltd., Tallinn, Estonia) was used to assess the mechanical properties of the medial gastrocnemius and Achilles tendon, including logarithmic decrement (elasticity), dynamic stiffness (stiffness), and oscillation frequency (tone).

Results: Data analysis revealed no significant relationships between fascicle length, pennation angle, or muscle thickness of the gastrocnemius and its mechanical properties ($p>.05$). Similarly, no significant associations were not found between Achilles tendon thickness and its mechanical characteristics ($p>.05$). However, the dynamic stiffness of the Achilles tendon showed a moderate positive correlation with body mass index ($r=.364$, $p=.003$), gastrocnemius thickness ($r=.278$, $p=.032$), pennation angle ($r=.285$, $p=.023$), and subcutaneous fat thickness ($r=.328$, $p=.009$).

Conclusion: This study demonstrated that muscle and tendon architecture does not directly determine their mechanical properties. However, higher body mass index, increased muscle thickness, and greater pennation angle may elevate the mechanical load on the tendon, potentially increasing Achilles tendon stiffness. These findings highlight the importance of considering anthropometric characteristics in addition to structural parameters when evaluating tendon and muscle mechanical properties.

Key Words: Stiffness, Elasticity, Tone, Muscle Architecture, Fascicle Length, Pennation Angle

ÖZ

Amaç: Bu çalışmanın amacı, gastroknemius kasının mimari özellikleri olan lif demeti uzunluğu, pennasyon açısı ve kas kalınlığı ile Aşil tendonunun kalınlığının; Gastroknemius kası ve Aşil tendonun mekanik özellikleri (elastikiyet, sertlik ve tonus) üzerindeki etkilerini incelemekti.

Yöntem: Çalışmaya, kas-iskelet sistemiyle ilgili herhangi bir semptomu olmayan,18-27 yaş aralığında, 63 sağlıklı gönüllü kadın katıldı. Gastroknemius kasının pennasyon açısı, kalınlığı ve lif demeti uzunluğu ile Aşil tendonu kalınlığı, lineer problu (5-12 MHz) bir ultrasonografi cihazı (MicrUs EXT-1H, Telemed Ultrasound Medical Systems, Vilnius, Litvanya) kullanılarak ölçüldü. Medial gastroknemius kası ve Aşil tendonunun mekanik özellikleri, taşınabilir bir miyotonometre (MyotonPRO, Myoton Ltd., Estonya) kullanılarak elastikiyetle ilişkili logaritmik azalma, sertlik göstergesi olan dinamik sertlik ve tonus göstergesi olan salınım frekansı ölçümleri gerçekleştirildi.

Bulgular: Veri analizinde, gastroknemius kasının lif demeti uzunluğu, pennasyon açısı ve kalınlığı ile mekanik özellikleri arasında anlamlı bir ilişki bulunmadı ($p>.05$). Benzer şekilde, Aşil tendonu kalınlığı ile tendonun mekanik özellikleri arasında da anlamlı bir ilişki olmadığı gözlendi ($p>.05$). Ancak, Aşil tendonunun dinamik sertliği; vücut kitle indeksi ($r=.364$, $p=.003$), gastroknemius kas kalınlığı ($r=.278$, $p=.032$), pennasyon açısı ($r=.285$, $p=.023$) ve subkutan yağ kalınlığı ($r=.328$, $p=.009$) ile orta düzeyde pozitif korelasyon gösterdi.

Sonuç: Bu çalışma, kas ve tendon mimarisine ait parametrelerin bu yapıların mekanik özellikleri üzerinde doğrudan belirleyici olmadığını göstermiştir. Ancak yüksek vücut kitle indeksi, artmış gastroknemius kas kalınlığı ve büyük pennasyon açısı gibi faktörlerin, tendon üzerine binen mekanik yükü artırarak Aşil tendonunun sertliğini artırabileceği sonucuna varılmıştır. Bu bulgular, kas ve tendonun mekanik özelliklerinin değerlendirilmesinde yalnızca yapısal-morfolojik ölçütlerin değil, bireyin genel vücut yapısını yansıtan antropometrik özelliklerin de dikkatle göz önünde bulundurulması gerektiğini göstermektedir.

Anahtar Kelimeler: Sertlik, Esneklik, Tonus, Kas Mimarisi, Lif Uzunluğu, Pennasyon Açısı

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INTRODUCTION

Mechanical properties such as tone, stiffness and elasticity of a muscle or tendon are important components of joint stability and/or control [1]. Tone is characterized by the intrinsic tension of the muscle at the cellular level in a passive or resting state without voluntary contraction [2]. Elasticity is defined as the ability of the tissue to return to its previous shape, which has been deformed due to an external force or contraction [3]. Stiffness refers to the ability of a tissue to resist external loading or contraction [4]. Evaluation of mechanical properties of a muscle or tendon is important for detecting changes in muscle or tendon function and structure. The rate and efficiency of the transmission of the force produced by the muscle to the bone over the joint via the tendon is related to the mechanical properties of the tendon [5]. Furthermore, mechanical properties of tendons and muscles are important parameters that affect the rate of force production and the rapid force development during a movement [6]. Moreover, it was reported that stiffness or tone of the tendon and/or muscle affects the range of motion of the related joint [7]. Furthermore, the evaluation of the mechanical properties of tendon and muscle may provide important information about the presence of a pathological condition or healing process related with this particular tendon or muscle. It was reported that the stiffness and tones [8] of the Achilles tendon are lower in patients with Achilles tendinopathy. Furthermore, Yoshida et al. [9] indicated that the gastrocnemius muscle stiffness decreases in individuals with gastrocnemius muscle injury.

Mechanical properties of a muscle or tendon can be measured by different methods such as Shear-Wave Elastography, Magnetic resonance imaging, or via myotonometers. Myotonometry has important advantages compared to the other methods. Myotonometric measurements are low-cost and take less time compared to Shear-Wave Elastography and/or Magnetic resonance imaging. On the other hand, Shear-Wave Elastography can evaluate only stiffness, and MRI can evaluate only elasticity; however, myotonometer can evaluate tone, stiffness, and elasticity.

With the technological developments in the last 10 years, the rapid, economical, and reliable measurement of muscle and tendon mechanical properties has increased the number of studies in this field dramatically. It is seen that an important portion of these studies aimed at determining the factors that affect the mechanical properties of tendons and muscles. For example, it was reported that males had a stiffer gastrocnemius muscle and Achilles tendon [10]. Moreover, it was reported that older individuals had a less stiff muscle and tendon [11,12]. Furthermore, it was indicated that higher body mass index and serum lipid concentration were related to a less stiff patellar tendon [13]. On the other hand, there are very limited studies investigating the effect of muscle architecture and subcutaneous fat tissue on tone, elasticity, and stiffness of muscles and tendons. Ikezoe et al. [11] reported that the thicknesses of the vastus intermedius and the rectus femoris muscles was correlated with the stiffness of the quadriceps femoris muscle; however, the overlying subcutaneous fat thickness was not correlated with muscle stiffness in elderly individuals. Chino et al. [14] indicated that there was a negative negligible correlation between rectus femoris thickness and passive rectus femoris stiffness in male athletes but not in female athletes. Agyapong-Badu et al. [15] found that overlying subcutaneous fat thickness was negatively correlated with the tone and stiffness of the rectus femoris. To our knowledge, there is no study investigating the relationship between muscle fascicle length and muscle pennation angle and muscle mechanical properties as well as the relationship between tendon mechanical properties and tendon thickness. Identifying the possible factors affecting the mechanical properties of tendons and muscles may help us better understand muscle and/or tendon functions. Therefore, the present study aimed to investigate the relationship of the fascicle length, pennation angle, and thickness of the gastrocnemius muscle and the thickness of the Achilles tendon with the tone, elasticity and stiffness of the Achilles tendon and the gastrocnemius muscle. Another purpose of this study was to investigate the effect of subcutaneous fat thickness on the mechanical properties of the gastrocnemius muscle. It was hypothesized that muscle and tendon architecture and subcutaneous fat thickness would affect their mechanical properties.

METHOD

Study Design and Participants

This research was conducted as a cross-sectional study. SPSS Sample Power 3.0 (IBM Corporation, Armonk, NY) software was used to calculate the sample size. Calculations were made by assuming the expected correlation coefficient as 0.40 and the desired power (β) as 80%. The alpha (α) value was accepted as 0.05. The estimated sample size for the study was at least 47 [16].

The present study was conducted in 63 sedentary females aged between 18 and 27 years (20.48±1.54 years). Participants who had not exercised regularly for at least 6 months prior to the study were considered sedentary [17]. Individuals were not included in the study if their body mass index (BMI) was ≥30 kg/m^2 because the reliability of myotometric measurements is less in obese individuals [18]. The exclusion criteria were: (1) having neurological diseases, (2) orthopaedic diseases such as tendinitis, bursitis, (3) history of surgery, major trauma or lower extremity fracture and (4) a systemic disease or connective tissue disorder. Before the evaluations, the content of the study was explained to the participants in detail, and verbal and written informed consent was obtained from each of them.

Outcome Measures

A portable myotonometer was used to measure the mechanical properties of the medial gastrocnemius muscle and Achilles tendon (MyotonPRO, Myoton Ltd., Tallinn, Estonia). MyotonPRO is a valid and reliable tool to measure the mechanical properties of muscles and tendons such as tone, stiffness, and elasticity [10,19,20]. This device applies a short-term (15 ms) and constant force (up to 0.6 N) to the tissue evaluated. Then, the MyotonPRO measures mechanical oscillations in the tissue. Measuring the oscillations in an assessed tissue gives the following data: (1) logarithmic decrement (related to elasticity), (2) oscillation frequency (indicator of tone), and (3) dynamic stiffness (indicator of stiffness).

The pennation angle, fascicle length and thickness of the gastrocnemius muscle and thickness of the Achilles tendon were measured using an ultrasonography device with a lineal probe (5–12 MHz) (MicrUs EXT-1H, Telemed Ultrasound Medical Systems, Vilnius, Lithuania). The ultrasonographic evaluations were made by an operator with 7 years of experience in the field of musculoskeletal ultrasonography. The ultrasound evaluations were performed in the myotometric measurement position on the dominant leg.

Data Collection

In mechanical properties measurements, all evaluations were performed by a physiotherapist with a 4-years experiences in myotometric measurements by the MyotonPRO. In order to determine the dominant limb, it was questioned with which leg they hit the ball. Before performing the measurements, the individuals rested for 5 min. The measurements were performed with the participants in the fully resting position. During the assessment, the females were positioned in the prone position on examination table, with the knee joint extended and the ankle in a neutral position. According to previous studies [10,21], the point 3 cm proximal of the superior aspect of the calcaneus was used to measure the mechanical properties of the Achilles tendon. Similar to previous studies [10,22], the measurements of the medial gastrocnemius muscles were performed on the plumpest point of the muscle which was defined as 70% distal of the lower leg length from the lateral malleolus to the popliteal fossa (Figure 1). The measurements were repeated 3 times and the mean values of 3 measurements were used for analysis.

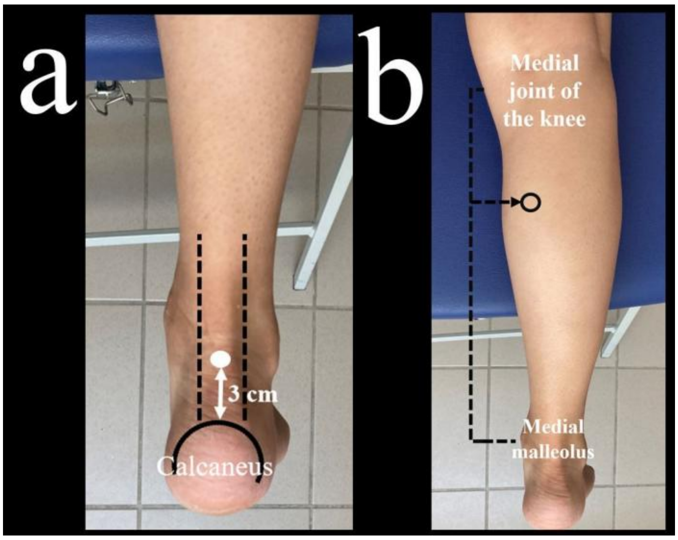

Figure 1. Locations of the myotonometric measurement: (a) the point 3 cm proximal of the superior aspect of the calcaneus was used to measure the mechanical properties of the Achilles tendon, (b) the measurements of the medial gastrocnemius muscles were performed on the plumpest point of the muscle which was defined as 70% distal of the lower leg length from the lateral malleolus to the popliteal fossa.

In ultrasonography assessments, the probe placed on the skin surface was adjusted to be parallel to the superficial and deep aponeuroses [23]. Probe placement was assumed to be correct if several fascicles on the ultrasound image were easily identifiable without any interruption and if the superficial and deep aponeuroses were parallel [24]. Images were taken three times, and the best fascicles were used to analyse the ultrasound images. Fascicle length was calculated as the length of an ultrasonic echo, parallel to the fascicles, between deep and superficial aponeuroses [25]. The angle between the muscle fascicle and the deep aponeurosis was used to calculate the pennation angle. Pennation angle was measured on three fascicles on the ultrasound image, and the mean value of these three measurements was calculated and used in the analysis [26] (Figure 2a). The distance between the superficial and deep aponeuroses was used to calculate muscle thickness. Muscle thickness was calculated by averaging three parallel lines drawn at right angles in the ultrasonographic image [24,27]. The linear distance between the deep border of the skin and the upper part of the superficial muscle fascia was calculated as the fat thickness [28] (Figure 2b). According to previous studies [29,30], Achilles tendon thickness measurements were taken at points 3 cm proximal to the superior aspect of the calcaneus (Figure 2c).

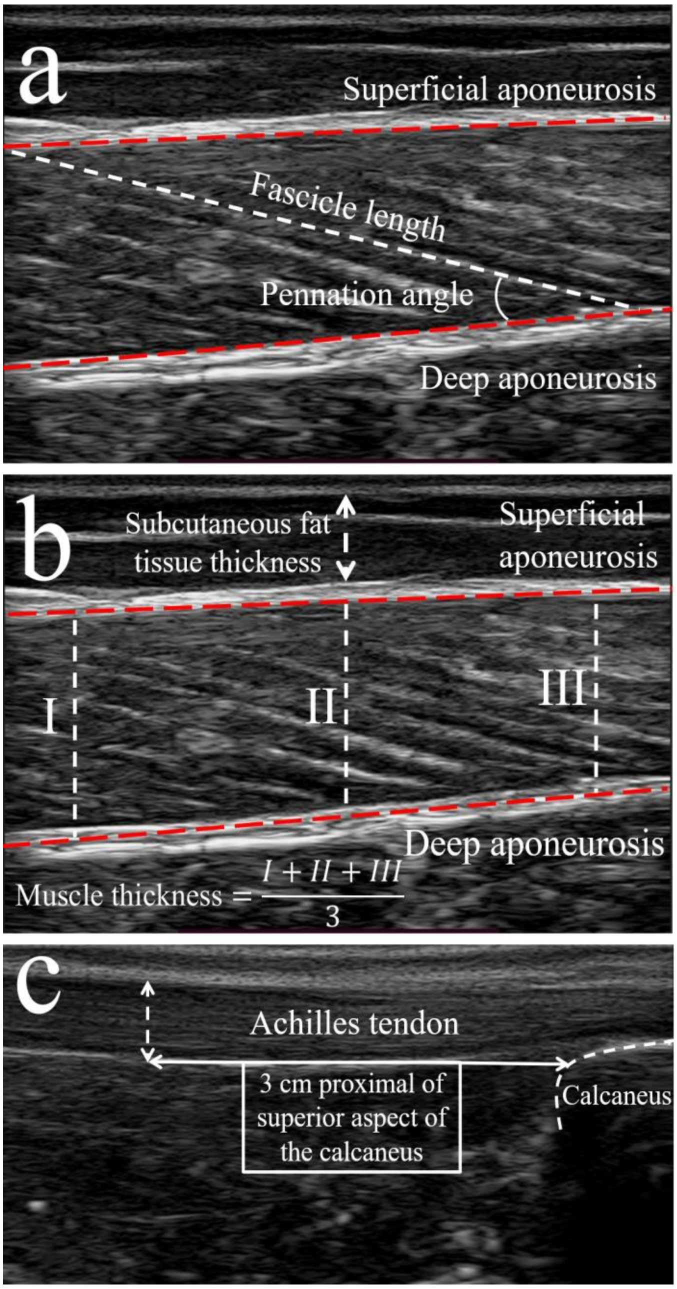

Figure 2. Ultrasonographic measurement: (a) The angle between the muscle fascicle and the deep aponeurosis was used to calculate the pennation angle. Fascicle length was calculated as the length of an ultrasonic echo, parallel to the fascicles, between deep and superficial aponeuroses, (b) The distance between the superficial and deep aponeuroses was used to calculate muscle thickness. The linear distance between the deep border of the skin and the upper part of the superficial muscle fascia was calculated as the fat thickness, (c) the measurements of the Achilles tendon thickness were performed at the points 3 cm proximal to the superior aspect of the calcaneus.

Ethical Approval

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Toros University (date: 27.05.2022, approval number: 101).

Statistical Analysis

IBM SPSS 25 (IBM SPSS Inc, Armonk, NY, USA) program was used in statistical analyses. Data were analysed for normality using the Kolmogorov–Smirnov/Shapiro–Wilk test and skewness and kurtosis coefficients. Since not all evaluated parameters showed normal distribution, minimum and maximum values, interquartile range (IQR), and median values were calculated.

Correlations between the evaluated parameters were determined using Spearman's test. The correlation results are classified as follows: 0.00-0.20 (poor), 0.21-0.40 (fair), 0.41-0.60 (moderate), 0.61-0.80 (strong) and 0.81-1.00 (very strong). Type I error level was set at 5% for statistical significance.

RESULTS

The demographic data of the participants and the results of the assessed parameters are given in Table 1.

Correlation analyses suggest that the fascicle length, pennation angle and thickness of the medial gastrocnemius muscle was not significantly correlated with the logarithmic decrement, dynamic stiffness, and oscillation frequency of the medial gastrocnemius muscle ($p>.05$). Similarly, Achilles tendon thickness was not correlated with the oscillation frequency ($r=-.014$, $p=.911$), dynamic stiffness ($r=0049$, $p=.704$), and logarithmic decrement ($r=-.087$, p=496) of the Achilles tendon. On the other hand, Achilles tendon dynamic stiffness had a fair correlation with body mass index (r= .364, p= .003), gastrocnemius thickness (r=.278, p=.032), pennation angle (r=.285, p=.023) and subcutaneous fat thickness (r=.328, p=.009) (Table 2).

Table 1. Median, interquartile range, minimum and maximum values of demographic data and assessed parameters

Parameters	**Median**	**Interquartile range**	**Min-Max**
Age (year)	20	20-21	18-27
Height (m)	1.64	1.58-1.69	1.50-1.79
Weight (kg)	56.9	51.2-61.1	40.1- 77.6
Body Mass Index (kg/m^2)	20.9	19.1-20.2	15.8- 29.5
Medial gastrocnemius			
Frequency (Hz)	15.0	13.8-15.8	12.5- 18.3
Stiffness (N/m)	252.8	237.3- 276.0	189.7- 333.7
Logarithmic decrement	1.0	0.9- 1.1	0.7- 1.3
Achilles tendon			
Oscillation frequency (Hz)	31.4	29.6- 32.4	26.3- 34.13
Dynamic Stiffness (N/m)	799.7	733.3-838.0	668.7- 898.0
Logarithmic decrement	0.7	0.7-0.8	0.7- 1.0
Medial gastrocnemius			
Muscle thickness (mm)	15.9	15.1-17.5	11.6- 22.2
Pennation angle (º)	19.7	18.4-22.3	14.4- 25.2
Fascicle length (mm)	44.2	41.0-48.3	33.7- 67.2
Achilles tendon			
Tendon thickness (mm)	4.3	3.9-4.6	3.2- 5.1
Subcutaneous fat tissue thickness (mm)	5.5	4.9-7.8	2.4- 9.9

DISCUSSION

To our knowledge, this is the first study investigating the relationship between muscle architecture, such as pennation angle and fascicle length and mechanical properties of muscles. It was hypothesised that fascicle length, thickness, and pennation angle of the medial gastrocnemius muscle would be related with elasticity, stiffness, and tone of the medial gastrocnemius muscle because muscle architecture is the main determinant of muscle function. Muscles with longer fascicle allow greater range of motion than muscles with shorter fascicle [31]. On the other hand, muscle pennation angle and thickness are directly related to the physiological cross-sectional area of the muscle [31], which is one of the essential parameters affecting the muscle's potential to generate force and resist external forces [32], and it may affect muscle mechanical properties such as stiffness and/or elasticity. Different from the hypothesis, the results indicated that muscle architecture features of the medial gastrocnemius muscle were not associated with the mechanical properties of the muscle. There are limited studies investigating the relationships between muscle thickness and muscle stiffness. Chino et al. [14] investigated the relationships between rectus femoris stiffness and thickness in athletes and non-athletes by Shear-Wave Elastography. Similar to our results, they reported that there was a negligible correlation between rectus femoris stiffness and thickness in male athletes, but muscle stiffness was not related with muscle thickness in female non-athletes, female athletes and male non-athletes [14]. Different from our results, Ikezoe et al. [11] indicated that rectus femoris stiffness had a strong correlation with rectus femoris thickness in the elderly. On the other hand, it was found that Achilles tendon thickness was not related to its stiffness and elasticity. Indeed, we hypothesized that a thicker tendon would be associated with a stiffer and less elastic tendon. The results obtained suggest that tendon morphological features do not affect the tendon mechanical properties.

The other finding of the study was that subcutaneous fat thickness did not affect the mechanical properties of the medial gastrocnemius muscle. There have been some attempts to investigate the effect of subcutaneous fat thickness on muscle mechanical properties. Similar to the present results, Ikezoe et al. [11] reported that overlaying subcutaneous fat did not affect rectus femoris stiffness. Moreover, Alfuraih et al. [33] found that subcutaneous fat thickness was not correlated with the stiffness of vastus lateralis and biceps femoris muscles. Different from our results, Agyapong-Badu et al. [15] found that overlying subcutaneous fat thickness was negatively correlated with the tone and stiffness of the rectus femoris. On the other hand, our results suggest that overlaying subcutaneous fat thickness and body mass index had a fair correlation with Achilles tendon stiffness. Increased load on the tendon due to high body mass may cause an increase in tendon stiffness by stimulating collagen synthesis in the tendon [34,35]. Similar to the present results, Tomlinson et al. [36] reported that body mass index was positively and strongly correlated with the cross-sectional area and stiffness of the Achilles tendon in young adults. Different from our results, it was reported that body fat percentage was negatively correlated with patellar tendon stiffness [37]. Al-Qahtani et al [38] reported that obese individuals had less stiff quadriceps tendon compared with participants with normal weight. The reason why we had different results from these studies in the literature may be related to the differences regarding the participants included in the study or the study designs. All these studies were case-control studies, and they compared tendon stiffness in normal weight and obese groups. However, the present study is a correlational study, and also almost all of the individuals participating in the study were normal weight individuals.

Another finding of this study revealed that the thickness and pennation angle of medial gastrocnemius muscle had a fair correlation with Achilles tendon stiffness. An important reason behind the relationship between the thickness and pennation angle of the medial gastrocnemius and Achilles tendon stiffness may be associated with increased loading on the Achilles tendon due to the higher pennation angle and thickness of the medial gastrocnemius muscle. It is well-known that higher penetration angle and thickness of a muscle are related to higher force generation [32,39]. Mechanical loading is essential for the continuation of the tendon homeostasis. The increased loading causes the formation of collagen fibres and a new extracellular matrix in the tendon, which increases the tendon stiffness [34,35,40]. An increase in tendon stiffness might be a mechanism to compensate toward reducing increased mechanical loadings on the tendon and the tendon deformation due to increased gastrocnemius muscle strength.

Limitations

The present study had some limitations. Firstly, this study was carried out with the participation of young women. The relationship between the parameters assessed may be different in male or in middle-aged or elderly individuals. Measurements performed in this study were made while the individuals were in the resting position. The relationships between the parameters examined under different muscle activities or tensions may be different. Thirdly, the thickness of the gastrocnemius muscle and Achilles tendons was measured at their longitudinal axis, and measurements of the cross-sectional area of the gastrocnemius muscle and Achilles tendon were not performed in the present study. It would provide more information if the cross-sectional area of the Achilles tendon and gastrocnemius muscle is measured.

Table 2. Correlation analysis results between parameters assessed

	Variables	Demographic data			Medial gastrocnemius							Achilles tendon			
		Weight	**Height**	**BMI**	**Thickness**	**Pennation angle**	**Fascicle length**	**Fat thickness**	**Oscillation frequency**	**Dynamic stiffness**	**Log. decrement**	**Thickness**	**Oscillation frequency**	**Dynamic stiffness**	**Log. decrement**
Demographic data	**Age**	- .123	.014	- .096	- .006	- .073	.097	- .027	- .167	- .077	.101	- .021	.138	.101	- .096
	Weight		**.358****	**.808****	**.354****	.233	**.252***	**.345****	.185	.186	**.254***	.041	**.288***	**.425****	.037
	Height			- .211	.099	- .158	.212	- .117	.239	**.282***	.059	**.411****	.073	.096	- .180
	BMI				**.351****	**.340****	.157	**.425****	.025	- .012	.190	- .202	.247	**.364****	.163
Medial gastrocnemius	**Muscle thickness**					**.405****	**.523****	- .010	.105	.051	.082	.184	.131	**.278***	.211
	Pennation angle						- .217	.183	.081	.082	.206	- .102	.188	**.285***	.093
	Fascicle length							- .166	.233	.090	- .100	.242	.059	.089	- .026
	Fat thickness								**- .326****	- .076	.170	- .163	.102	**.328****	- .008
	Oscillation frequency									**.792****	- .101	.090	- .024	.053	- .062
	Dynamic stiffness										- .027	.005	.105	.180	- .135
Achilles tendon	**Logarithmic decrement**											.021	- .003	.066	.144
	Tendon thickness												- .014	.049	- .087
	Oscillation frequency													**.811****	- .046
	Dynamic stiffness														**- .281***

**p<.05, **p<.01*

CONCLUSION

It was found that the fascicle length, pennation angle and thickness of the medial gastrocnemius muscle did not affect the elasticity, tone, and/or stiffness of the medial gastrocnemius muscle. Furthermore, Achilles tendon thickness was not related to the elasticity and stiffness of the Achilles tendon. Moreover, overlaying subcutaneous fat thickness was not correlated with the stiffness, and elasticity of the medial gastrocnemius muscle. On the other hand, higher body mass index and overlaying subcutaneous fat thickness was related to decreased Achilles tendon stiffness. In addition, there was a positive correlation between pennation angle and thickness and Achilles tendon stiffness in young females. Further studies are needed to investigate the parameters assessed in male, middle-aged or elderly individuals.

Ethical Approval: *2022/101 Toros University Scientific Research Ethics Committee*

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