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Muscle Architecture Symmetry and Functional Performance in Healthy Young Adults Assessed by Ultrasonography and Field Tests: Cross-Sectional Study

Sağlıklı Genç Erişkinlerde Kas Mimarisi Simetrisi ve Fonksiyonel Performansın Ultrasonografi ve Alan Testleri ile Değerlendirilmesi: Kesitsel Araştırma

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ABSTRACT Objective: To compare muscle architecture, ankle strength, joint mobility, and functional performance between dominant and non-dominant lower limbs in healthy young adults, and to examine associations between ultrasonographic architecture and field-based functional tests. **Material and Methods:** Twenty-four (11 males, 13 females; mean age: 24.1±2.1 years) healthy adults underwent bilateral ultrasound of medial/lateral gastrocnemius, tibialis anterior, and Achilles tendon to assess muscle thickness, pennation angle, and fascicle length. Ankle strength was tested via handheld dynamometry. Functional performance included heel-rise height and repetitions, lunge, hop, and jump tests. Wilcoxon signed-rank test and Spearman correlations (r) with r^2 were calculated. **Results:** No significant side-to-side differences were found (all $p>0.05$). In the dominant limb, medial gastrocnemius thickness correlated with dorsiflexor strength ($r=0.642$, $p<0.001$) and heel-rise repetitions ($r=0.448$, $p=0.047$); medial gastrocnemius pennation angle related to dorsiflexor strength ($r=0.463$, $p=0.023$) and endurance ($r=0.556$, $p=0.011$). Tibialis anterior pennation angle was linked to vertical jump ($r=0.567$, $p=0.004$) and heel-rise height ($r=0.549$, $p=0.005$). Achilles thickness correlated with jump ($r=0.572$, $p=0.003$). In the non-dominant limb, tibialis anterior thickness correlated with repetitions ($r=0.607$, $p=0.005$) and single-leg hop ($r=0.436$, $p=0.033$); lateral gastrocnemius pennation angle was inversely related to plantarflexor strength ($r=-0.455$, $p=0.025$). **Conclusion:** Despite symmetry, muscle thickness and pennation angle showed moderate correlations with function, supporting their clinical relevance.

Keywords: Muscle strength; muscle strength dynamometer; physical functional performance; ultrasonography

ÖZET Amaç: Sağlıklı genç erişkinlerde, dominant ve nondominant alt ekstremiteler arasında kas mimarisi, ayak bileği kas kuvveti, eklem hareket açıklığı ve fonksiyonel performansı karşılaştırmak; ayrıca ultrasonografik kas mimarisi ile alan temelli fonksiyonel testler arasındaki ilişkileri incelemektir. **Gereç ve Yöntemler:** Yirmi dört (11 erkek, 13 kadın; ortalama yaş: 24,1±2,1 yıl) sağlıklı erişkin mediyal/lateral gastroknemius, tibialis anterior ve Aşil tendonunun kas kalınlığı, pennasyon açısı ve fasikül uzunluğunu değerlendirmek için bilateral ultrasonografi ile incelendi. Ayak bileği kas kuvveti el dinamometresi ile ölçüldü. Fonksiyonel performans; parmak ucuna yükselme yüksekliği ve tekrar sayısı, diz-duvar testi, sekme ve sıçrama testleri ile değerlendirildi. İstatistiksel analizde, Wilcoxon işaretli sıralar testi ile Spearman korelasyon katsayıları (r) ve r^2 değerleri hesaplandı. **Bulgular:** Ekstremiteler arasında anlamlı fark bulunmadı (tüm $p>0,05$). Baskın tarafta mediyal gastroknemius kalınlığı, dorsifleksiyon kuvveti ($r=0,642$, $p<0,001$) ve parmak ucuna yükselme tekrar sayısı ($r=0,448$, $p=0,047$) ile ilişkiliydi. Mediyal gastroknemius pennasyon açısı, dorsifleksiyon kuvveti ($r=0,463$, $p=0,023$) ve endurans ($r=0,556$, $p=0,011$) ile ilişkiliydi. Tibialis anterior pennasyon açısı, dikey sıçrama ($r=0,567$, $p=0,004$) ve parmak ucuna yükselme seviyesi ($r=0,549$, $p=0,005$) ile ilişkiliydi. Aşil tendonu kalınlığı dikey sıçrama performansı ile ilişkiliydi ($r=0,572$, $p=0,003$). Baskın olmayan tarafta tibialis anterior kalınlığı, parmak ucuna yükselme tekrar sayısı ($r=0,607$, $p=0,005$) ve tek bacak sekme testi performansı ($r=0,436$, $p=0,033$) ile ilişkiliydi. Lateral gastroknemius pennasyon açısı ise plantarfleksiyon kuvveti ile ters yönlü ilişkiliydi ($r=-0,455$, $p=0,025$). **Sonuç:** Ekstremiteler arasındaki simetriye rağmen kas kalınlığı ve pennasyon açısı fonksiyonla orta düzeyde ilişkiler gösterdi; bu bulgular, söz konusu parametrelerin klinik açıdan anlamlı olabileceğini desteklemektedir.

Anahtar Kelimeler: Kas kuvveti; kas gücü dinamometresi; fiziksel fonksiyonel performans; ultrasonografi

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The functional capacity of skeletal muscle is largely influenced by its architectural design, which includes parameters such as fiber length, pennation angle, and physiological cross-sectional area (PCSA).[1] These components collectively determine a muscle's ability to produce force and contract at varying velocities, depending on structural configuration.[1-3] Notably, pennation angle enhances force-generating capacity by allowing a greater number of fibers to attach obliquely to the tendon, thereby increasing PCSA.[1,2] However, this configuration may reduce the muscle's shortening speed.[4]

Despite a growing interest in muscle architecture, the literature presents inconsistent findings regarding its association with functional output. In particular, studies investigating vastus lateralis have reported both positive and non-significant correlations between pennation angle and peak power output. While muscle volume and PCSA have been shown to strongly predict force generation in some studies, these relationships appear to vary across different muscle groups and task demands.[5-9] Furthermore, the reliability of using fiber length and pennation angle to infer functional capacity remains uncertain, particularly in untrained or non-athletic populations.[10,11]

The lower limb muscles, particularly the triceps surae and tibialis anterior (TA), have been frequently studied in the context of walking, jumping, and postural control.[8,12-16] The medial gastrocnemius and lateral gastrocnemius (MG and LG) are characterized by obliquely oriented fascicles, measurable pennation angles, and variable muscle thickness, whereas the TA demonstrates a distinct unipennate architecture with regional differences in fascicle organization and thickness.[10,12-15,17,18] In addition, the Achilles tendon functions as the primary force-transmitting structure of the triceps surae.[17] Together, these morphological features, including muscle thickness, fascicle length, and pennation angle, may contribute to variations in lower-limb strength and functional performance. However, their architectural contribution to functional performance especially in terms of endurance (e.g., heel-rise repetitions) and explosive power (e.g., vertical jump) is still not fully understood. Existing evidence suggests that pennation angle and muscle thickness may influence strength and endurance performance, whereas fascicle length appears to have a more variable or negligible impact.[8,12,13]

Moreover, previous studies have largely overlooked the potential influence of limb dominance. Although some neuromuscular asymmetries have been reported between dominant and non-dominant limbs, the evidence for morphological or architectural asymmetry in healthy individuals remains limited.[16-18] If functional performance is closely linked to architectural parameters, one might expect subtle differences across limbs; yet whether such differences are detectable in non-athletic populations remains unclear.

Therefore, the objective of the present study was to compare dominant and non-dominant lower limbs in terms of muscle architecture, muscle strength, and functional performance in healthy individuals, and to investigate whether lower-limb architectural parameters are associated with muscle strength and functional performance test outcomes.

MATERIAL AND METHODS

STUDY DESIGN

The study was approved by the Institutional Ethics Committee of Hacettepe University (date: April 6, 2021; no: GO 21/475). The study was conducted at the Department of Physiotherapy and Rehabilitation, Faculty of Physical Therapy and Rehabilitation, Hacettepe University, Ankara, Türkiye. Written informed consent was obtained from all subjects, and all procedures were in accordance with the Declaration of Helsinki. Data were obtained between May 2022 and May 2024. A priori power analysis using G*Power software version 3.1.9.2 (University of Kiel, Germany) indicated that a minimum of 12 participants would be required to detect a moderate effect size (0.40) with 80% power at an alpha level of 0.05.

Participants

The study included 24 young healthy individuals, comprising 11 males and 13 females (mean age: 24.1±2.1 years; body mass index: 22.6±2.8 kg/m²). All participants underwent a standardized assessment and completed a questionnaire to obtain demographic characteristics and sports-related information. Limb dominance was determined based on the participant's preferred leg for kicking a ball.

Inclusion and Exclusion Criteria

The inclusion criteria were an age between 20 and 35 years and no participation in professional sports. The exclusion criteria were a history of lower-limb injury or surgery, foot or ankle deformity, neurological or musculoskeletal disorders involving the ankle or knee joint, any condition limiting walking ability, lower-limb pain, corticosteroid or hydrodilatation injection within the previous 3 months, or lower-extremity physical therapy within the previous 6 months.

Ultrasound Imaging of Muscle Architecture

Ultrasonographic assessment was performed on 3 lower-leg muscles, namely the MG, LG, and TA, together with the Achilles tendon. Muscle thickness, fascicle length, and pennation angle of each muscle, as well as Achilles tendon thickness, were examined using B-mode ultrasonography (Shimadzu SDU-1200 Pro, Osaka, Japan) equipped with a linear array transducer operating at 5-10 MHz. All ultrasound examinations were conducted by the same examiner, who had over 10 years of experience in musculoskeletal ultrasonography.

For image acquisition, the probe was positioned at standardized anatomical landmarks: at 30% of the distance between the popliteal crease and the medial malleolus for the MG, at 30% of the distance between the popliteal crease and the lateral malleolus for the LG, and at 20% of the distance between the fibular head and the lateral malleolus for the TA. These locations were selected because they correspond to regions where the muscle cross-sectional area is known to be maximal.[19,20]

During imaging of the MG and LG, participants lay prone with the knee fully extended and the ankle maintained in a neutral position (90°).[15] For evaluation of the TA, participants were positioned supine with the knee in slight flexion and the ankle similarly maintained in a neutral position (90°).[21] To improve measurement reliability and reduce the likelihood of oblique sampling, the transducer was aligned parallel to the muscle fascicles and held perpendicular to the skin surface. Two images were obtained from each measurement site, and the mean of the 2 measurements was used for analysis. After completing measurements on one limb, the same protocol was applied to the contralateral side.

Muscle thickness was defined as the linear distance between the internal borders of the superficial and deep aponeuroses.[22] Pennation angle was calculated as the angle formed between the muscle fascicle and the deep aponeurosis, while fascicle length was determined as the distance from the point where the fascicle originated at the superficial aponeurosis to its insertion into the deep aponeurosis.[23] All images were exported to ImageJ software (Image J 1.43u; National Institutes of Health, Bethesda, Maryland, USA), where measurements of fascicle length, pennation angle, and muscle thickness were performed.

Assessment of Muscle Strength

Isometric strength of the ankle dorsiflexor and plantarflexor muscles was evaluated using a hand-held dynamometer (Lafayette Model 01165; Lafayette Instrument Company, Lafayette, IN, USA). All measurements were conducted with participants seated, the knees fully extended, and the tested limb stabilized proximally at the ankle joint. To limit compensatory movements, participants were positioned facing a wall and instructed to keep their hands crossed over the chest throughout the procedure.

For dorsiflexion testing, the dynamometer was applied to the dorsal aspect of the foot, just proximal to the metatarsal heads. During plantarflexion assessment, the device was placed on the plantar surface of the foot, immediately proximal to the first metatarsal heads. Participants were asked to exert maximal voluntary force against the dynamometer and maintain the contraction for 5 seconds. Each measurement consisted of 3 maximal isometric contractions, each lasting 5 seconds, with the mean value of the 3 trials used for subsequent analyses.[24]

Functional Performance Tests

All functional tests were conducted on both dominant and non-dominant limbs, with at least 1-minute rest between trials to prevent fatigue.

Heel rise test

The heel-rise test was performed in a standing position with the knee fully extended and body weight supported on the forefoot of the tested limb. Partici-

pants were instructed to rise onto the toes as high as possible. Heel-rise height was measured, and the test was repeated 3 times. The highest value was recorded for analysis.[25]

1-Minute heel-rise repetition test

For the 1-minute heel-rise test, participants were asked to perform as many heel rises as possible within 60 seconds while maintaining proper form. The total number of repetitions was recorded.[25]

Weight Bearing Lunge Test

The weight-bearing lunge test was employed to assess ankle dorsiflexion range of motion. This procedure is considered a valid and reliable functional method that indirectly quantifies dorsiflexion by evaluating anterior tibial translation over the hindfoot, with excellent reported reliability [intraclass correlation coefficient: 0.97 (ICC)].[26] Testing was performed with participants standing and facing a wall. The tested foot was positioned parallel to a tape measure fixed to the floor, ensuring alignment of the second toe, the center of the heel, and the knee in a vertical line toward the wall. Participants were instructed to advance into a forward lunge, flexing the knee until it made contact with the wall, while maintaining full heel contact with the ground. When successful contact was achieved, the foot was repositioned 1 cm farther from the wall and the maneuver was repeated. This incremental progression continued until the participant was no longer able to touch the knee to the wall without lifting the heel. The final measurement was recorded in centimeters as the maximum distance from the foot position at which knee-to-wall contact could be maintained.[26]

Single-Leg Hop for Distance

Participants were instructed to perform a maximal forward hop, taking off and landing on the same limb. Each participant completed 3 trials, and the longest hop distance achieved was recorded in centimeters for analysis.[21]

Vertical Jump Test

Explosive lower limb power was evaluated using the vertical jump test. Colored chalk was applied to the participant's fingertip, and participants first marked their standing reach height on a wall. Then, from a stationary position (no step or arm swing), they performed a maximal vertical jump and made a second mark with their fingertip. Jump height was calculated as the distance between the 2 marks. This method has been shown to be simple, reliable (ICC=0.93), and objective (ICC=0.93). The test was repeated 3 times, and the average value was used.[27]

STATISTICAL ANALYSIS

Statistical procedures were performed using IBM SPSS Statistics software (version 21.0; IBM Corp., Armonk, NY, USA). Descriptive data are presented as mean values accompanied by standard deviations. Distributional characteristics of the variables were evaluated by examining histograms and Q-Q plots, and normality was further tested using the Shapiro-Wilk method.

Depending on the distribution of each variable, the Wilcoxon signed-rank test was used to compare dominant and non-dominant limbs. Associations between muscle architecture and strength or functional performance measures were analyzed using Spearman correlation coefficients (ρ) due to non-normal distribution of variables. For all statistically significant correlations, coefficients of determination (r^2) were calculated to express the proportion of explained variance.[28] The significance level was set at $p<0.05$ for all analyses. Additionally, Symmetry Index (%) was calculated to quantify the degree of asymmetry between dominant and non-dominant limbs.[29]

The formula used was:

$$\text{Symmetry Index (\%)} = \left(\frac{\frac{\text{Dominant}-\text{non}-\text{dominant}}{(\text{Dominant}+\text{non}-\text{dominant})}}{2}\right) x100$$

Positive values indicate higher measurements on the dominant side, while negative values indicate higher measurements on the non-dominant side.

RESULTS

Participant demographics are presented in Table 1. Twenty-four healthy individuals (mean age: 24.1±2.1 years; 11 males, 13 females) were included in the study. Among them, 22 had right lower limb dominance.

TABLE 1: Individuals demographic characteristics results are presented

Variables	Individuals (n=24) X̄±SD
Age (year)	24.1±2.1
Height (cm)	172.3±8.8
Weight (kg)	67.2±11.2
BMI (kg/m^2)	22.6±2.8
Dominant side (right/left)	22/2
Gender (male/female)	11/13

SD: Standard deviation; BMI: Body mass index

BETWEEN-LIMB COMPARISONS

As shown in Table 2, no significant differences were found between the dominant and non-dominant limbs regarding Achilles tendon thickness (p=0.170), and muscle thickness values for the MG (p=0.977), LG (p=0.841), and TA (p=0.493). Similarly, pennation angle (MG: p=0.301; LG: p=0.407; TA: p=0.407) and fascicle length (MG: p=0.658; LG: p=0.498; TA: p=0.687) did not differ between limbs. No significant side-to-side differences were observed in isometric dorsiflexor (p=0.407) or plantarflexor strength (p=0.265). Furthermore, no significant limb differences were found in functional performance tests, including heel-rise height (p=0.721), weight-bearing lunge test (p=0.241), and single-leg hop test (p=0.548).

Additionally, symmetry indices (%) were calculated for all relevant variables and presented in Table 2 to quantify side-to-side asymmetry.

FUNCTIONAL RELEVANCE OF MUSCLE ARCHITECTURE

Dominant Extremity

In the dominant limb, several significant correlations were observed between muscle architectural features and strength or functional performance parameters. A strong positive association was found between MG thickness and dorsiflexor strength (r=0.642, p<0.001; r^2=0.41) (Table 3). MG pennation angle was also positively correlated with dorsiflexor strength (r=0.463, p=0.023; r^2=0.21) (Table 3). In addition, MG thickness (r=0.448, p=0.047; r^2=0.20) and MG pennation angle (r=0.556, p=0.011; r^2=0.31) were significantly associated with heel-rise endurance, measured as the

TABLE 2: Comparison of muscle architecture and strength parameters between dominant and non-dominant limbs with Symmetry Index analysis

Variables		Dominant (n=24) Median (IQR)	Non-dominant (n=24) Median (IQR)	p value	Dominant (n=24) X̄±SD	Non-dominant (n=24) X̄±SD	Symmetry Index (%)
Ankle dorsiflexor strength (N)		225.7 (190.4-268.3)	224 (176.7-250.6)	0.407	236.74±73.79	230.94±76.73	2.48
Ankle plantar flexor strength (N)		314.2 (214.2-371.7)	305.5 (192-391)	0.265	301.79±94.73	309.35±111.46	-2.47
Heel rise (cm)		11.9 (10.7-12.7)	11.6 (10.1-13.3)	0.721	11.72±2.15	11.64±2.20	0.69
WBLT (cm)		12.5 (10.6-14.9)	12.3 (9.6-14.4)	0.241	12.58±2.69	12.27±2.67	2.50
Single leg hop test (cm)		131 (110.7-180.7)	130.4 (106.2-182.8)	0.548	143.55±36.94	143.33±44.60	0.15
Thickness (mm)	AT	5.3 (4.8-6.1)	5 (4.5-5.5)	0.170	5.41±0.94	5.26±1.07	2.81
	MG	17.1 (16.2-21.3)	17.1 (15.7-21.8)	0.977	18.58±3.95	18.35±3.99	1.25
	LG	14.5 (12.9-17.6)	14.2 (11.4-16.3)	0.841	15.13±3.32	14.72±3.63	2.75
	TA	25.1 (22.7-27.1)	24.4 (22.9-26.3)	0.493	25.05±3.20	24.71±3.00	1.37
Pennation angle (degrees)	MG	22.8 (21.1-25.3)	23.4 (21.1-27.1)	0.301	23.33±3.56	24.17±3.58	-3.54
	LG	18 (17.2-20.1)	19.3 (16.8-21.5)	0.407	18.73±2.41	19.27±2.82	-2.84
	TA	12.6 (10.2-13.7)	12.6 (11.5-14.1)	0.407	12.33±2.41	12.91±2.52	-4.6
Fascicle length (mm)	MG	26.4 (21.5-45.2)	27.8 (22.2-39.3)	0.658	35.5±17.9	37.4±23.2	-5.2
	LG	26.1 (21.5-33.3)	23.8 (15.9-39.9)	0.498	36.54±33.48	36.57±29.94	-0.08
	TA	41.7 (29.7-50.2)	36.6 (28-50.9)	0.687	41.2±66.1	40.8±21.6	0.98

IQR: Interquartile range; SD: Standard deviation; N: Newton; WBLT: Weight Bearing Lunge Test; AT: Achilles tendon; MG: Gastrocnemius medialis; LG: Gastrocnemius lateralis; TA: Tibialis anterior; *p<0.05.

TABLE 3: Correlation between muscle architecture (dominant limb) and strength/functional performance (n=24)

Variables	Heel-rise height (cm)	WBLT (cm)	Single-leg hop (cm)	Dorsiflexor strength (N)	Plantarflexor strength (N)	Heel-rise reps (1 min)	Vertical jump height (cm)
AT thickness (mm)	r=0.328, p=0.118	r=0.098, p=0.649	r=0.216, p=0.312	r=0.069, p=0.750	r=-0.078, p=0.716	r=0.271, p=0.248	**r=0.572**, p=0.003 r^2=0.33 (33%)**
MG thickness (mm)	r =-0.201, p=0.346	r=0.252, p=0.235	r=0.289, p=0.171	**r=0.642**, p<0.001 r^2=0.41 (41%)**	r=0.323, p=0.123	**r=0.448*, p=0.047 r^2=0.20 (20%)**	r=-0.106, p=0.622
MG pennation angle (°)	r=0.226, p=0.288	r=0.150, p=0.485	r=0.071, p=0.741	**r=0.463*, p=0.023 r^2=0.21 (21%)**	r=0.45, p=0.834	**r=0.556*, p=0.011 r^2=0.31 (31%)**	r=0.014, p=0.947
MG fascicle length (mm)	r=0.77, p=0.728	r=-0.228, p=0.296	r=-0.45, p=0.837	r=0.326, p=0.129	r=0.084, p=0.703	r=0.344, p=0.149	r=-0.061, p=0.783
LG thickness (mm)	r=0.27, p=0.899	r=-0.174, p=0.417	r=-0.213, p=0.318	r=0.177, p=0.407	r=-0.173, p=0.419	r=0.071, p=0.767	r=-0.246, p=0.247
LG pennation angle (°)	r=0.179, p=0.402	r=-0.134, p=0.533	r=0.144, p=0.501	r=0.109, p=0.613	r=-0.013, p=0.952	r=0.167, p=0.481	r=0.043, p=0.843
LG fascicle length (mm)	r =-0.054, p=0.805	r=0.003, p=0.987	r=0.090, p=0.683	r=0.213, p=0.328	r=-0.039, p=0.861	r=0.157, p=0.521	r=-0.214, p=0.328
TA thickness (mm)	r=-0.033, p=0.880	**r=0.491*, p=0.015 r^2=0.24 (24%)**	r=0.324, p=0.122	r=0.124, p=0.563	r=-0.288, p=0.172	r=0.152, p=0.522	r=0.165, p=0.442
TA pennation angle (°)	**r=0.549**, p=0.005 r^2=0.30 (30%)**	r=0.110, p=0.610	r=0.335, p=0.110	r=0.021, p=0.923	**r=0.417*, p=0.043 r^2=0.17 (17%)**	r=0.169, p=0.477	**r=0.567**, p=0.004 r^2=0.32 (32%)**
TA fascicle length (mm)	r=-0.257, p=0.304	r=0.228, p=0.364	r=0.253, p=0.311	r=0.276, p=0.268	r=0.422, p=0.081	r=-0.189, p=0.499	r=0.323, p=0.191

WBLT: Weight Bearing Lunge Test; AT: Achilles tendon; N: Newton; MG: Gastrocnemius medialis; LG: Gastrocnemius lateralis; TA: Tibialis anterior; r^2 values represent the proportion of variance explained by the muscle architecture variable. For interpretability, r^2 is also presented as a percentage; p<0.05.

number of repetitions performed in 1 minute (Table 3). TA architecture also contributed significantly: TA thickness was associated with greater dorsiflexion range of motion as assessed by the WBLT (r=0.491, p=0.015; r^2=0.24), while TA pennation angle correlated positively with heel-rise height (r=0.549, p=0.005; r^2=0.30) and vertical jump performance (r=0.567, p=0.004; r^2=0.32) (Table 3). Interestingly, TA pennation angle also showed a moderate positive correlation with plantarflexor strength (r=0.417, p=0.043; r^2=0.17), suggesting that architectural characteristics of the TA may also be linked to broader ankle performance patterns beyond isolated dorsiflexor function (Table 3). Lastly, Achilles tendon thickness demonstrated a significant positive correlation with vertical jump height (r=0.572, p=0.003; r^2=0.33), reinforcing its importance in explosive lower-limb activities (Table 3).

Non-Dominant Extremity

In the non-dominant limb, several significant associations were also identified, particularly involving the TA and gastrocnemius muscles. TA thickness showed strong positive associations with heel-rise endurance (number of repetitions in one minute) (r=0.607, p=0.005; r^2=0.37) and single-leg hop distance (r=0.436, p=0.033; r^2=0.19) (Table 4). MG thickness was also significantly correlated with dorsiflexor strength (r=0.437, p=0.033; r^2=0.19), albeit to a lesser extent (Table 4). Moreover, Achilles tendon thickness exhibited a moderate negative correlation with plantarflexor strength (r=-0.467, p=0.022; r^2=0.22), a finding mirrored by a similar inverse relationship between LG pennation angle and plantarflexor strength (r=-0.455, p=0.025; r^2=0.21) (Table 4). These inverse relationships may indicate side-specific variations in force generation mechanisms on the non-dominant side.

Taken together, these findings demonstrate overall architectural and functional symmetry between limbs, while select muscle

TABLE 4: Correlation between muscle architecture (non-dominant limb) and strength/functional performance (n=24)

Variables	Heel-rise height (cm)	WBLT (cm)	Single-leg hop (cm)	Dorsiflexor strength (N)	Plantarflexor strength (N)	Heel-rise reps (1 min)	Vertical jump height (cm)
AT thickness (mm)	r=0.176, p=0.411	r=0.271, p=0.200	r=0.135, p=0.530	r=-0.172, p=0.421	**r=-0.467*, p=0.022 r^2=0.22 (22%)**	r=0.078, p=0.745	r=0.301, p=0.153
MG thickness (mm)	r=-0.335, p=0.110	r=-0.102, p=0.635	r=0.121, p=0.574	**r=0.437*, p=0.033 r^2=0.19 (19%)**	r=0.344, p=0.100	r=0.328, p=0.158	r=-0.194, p=0.363
MG pennation angle (°)	r=-0.131, p=0.540	r=-0.257, p=0.226	r=0.085, p=0.692	r=-0.093, p=0.665	r=-0.006, p=0.979	r=-0.056, p=0.816	r=0.174, p=0.416
MG fascicle length (mm)	r=-0.059, p=0.793	r=-0.246, p=0.270	r=0.038, p=0.867	r=0.207, p=0.355	r=0.334, p=0.129	r=-0.131, p=0.604	r=0.212, p=0.343
LG thickness (mm)	r=-0.354, p=0.090	r=0.173, p=0.419	r=-0.140, p=0.514	r=0.388, p=0.061	r=0.033, p=0.878	r=0.062, p=0.794	r=-0.320, p=0.127
LG pennation Angle (°)	r=0.063, p=0.770	r=-0.140, p=0.514	r=-0.339, p=0.105	r=-0.292, p=0.166	**r=-0.455*, p=0.025 r^2=0.21 (21%)**	r=-0.151, p=0.524	r=-0.108, p=0.616
LG fascicle length (mm)	r=0.160, p=0.465	r=-0.101, p=0.646	r=0.147, p=0.503	r=-0.165, p=0.452	r=-0.033, p=0.881	r=0.082, p=0.740	r=-0.029, p=0.897
TA thickness (mm)	r=0.195, p=0.360	r=0.174, p=0.417	**r=0.436*, p=0.033 r^2=0.19 (19%)**	r=0.323, p=0.123	r=-0.024, p=0.910	**r=0.607**, p=0.005 r^2=0.37 (37%)**	r=0.208, p=0.329
TA pennation angle (°)	r=0.192, p=0.368	r=0.241, p=0.257	r=0.169, p=0.431	r=0.200, p=0.349	r=-0.016, p=0.941	r=0.237, p=0.314	r=0.317, p=0.131
TA fascicle length (mm)	r=0.217, p=0.345	r=0.046, p=0.842	r=0.129, p=0.579	r=-0.079, p=0.733	r=-0.179, p=0.437	r=0.329, p=0.197	r=0.073, p=0.754

WBLT: Weight Bearing Lunge Test; N: Newton; AT: Achilles tendon; MG: Gastrocnemius medialis; LG: Gastrocnemius lateralis; TA: Tibialis anterior; r^2 values represent the proportion of variance explained by the muscle architecture variable. For interpretability, r^2 is also presented as a percentage; p<0.05

parameters, particularly TA and gastrocnemius characteristics, exhibit moderate correlations with strength and performance outcomes, emphasizing their functional relevance.

DISCUSSION

This study aimed to compare muscle architecture and functional performance between dominant and non-dominant limbs in healthy individuals, and to explore the relationship between architectural features and strength or performance outcomes. These results support the study objective by confirming architectural symmetry across limbs and revealing moderate associations between specific muscle parameters and functional outcomes. Additionally, strength and performance tests including isometric plantarflexor and dorsiflexor strength, heel-rise height and repetitions, vertical jump, WBLT, and single-leg hop did not differ significantly between sides. These findings are consistent with previous studies that reported no architectural or functional asymmetries in healthy individuals without sport-specific lower limb dominance.[14,16,30,31] Differences between studies may be related to variations in training status, age, athletic specialization, and the specific functional tests used. In particular, sport-specific loading and neuromuscular adaptations may increase side-to-side architectural or performance asymmetries, whereas such asymmetries may remain minimal in non-athletic young adults. Unlike most previous studies that focused on single muscle groups or isolated tests, our study incorporated a broader spectrum of static and dynamic performance tests including heel-rise height and repetitions, vertical jump, WBLT, and single-leg hop and simultaneously assessed architectural features of multiple lower extremity muscles (TA, MG, and LG). The inclusion of both sexes within a non-athletic young adult sample may improve the applicability of these findings to clinical and sports rehabilitation settings; however, the absence of sex-based analyses should be considered when interpreting this potential generalizability.

Moreover, calculated symmetry index values ranged between -5.2% and +2.8% across all strength and architectural parameters, reinforcing the high level of bilateral symmetry in this healthy sample.

Importantly, beyond inter-limb comparisons, the study also revealed moderate and significant correlations between specific muscle architecture parameters and functional performance. In the dominant limb, TA pennation angle was associated with vertical jump height (r=0.567), heel-rise height (r=0.549), and plantarflexor strength (r=0.417), accounting for 17-32% of the variance. MG thickness and pennation angle were correlated with dorsiflexor strength and heel-rise endurance (r=0.642 and r=0.556, respectively). In the non-dominant limb, TA thickness strongly predicted heel-rise repetitions (r=0.607) and single-leg hop distance (r=0.436). These results suggest that despite architectural symmetry across limbs, localized muscle characteristics particularly in the TA and gastrocnemius may partially explain individual variability in performance. The associations observed in both the TA and MG also suggest that functional performance may depend not only on isolated muscle characteristics but also on the coordinated contribution of agonist and antagonist muscle groups around the ankle.

The present findings contribute to a nuanced understanding of muscle architecture. While fascicle length showed no significant relationship with strength or function, pennation angle and thickness emerged as the most functionally relevant parameters, consistent with prior reports highlighting their roles in force transmission and mechanical efficiency.[8,12,13] These findings are also in line with earlier studies suggesting that pennation angle and muscle thickness may be more functionally informative than fascicle length in explaining strength- and performance-related outcomes. The lack of association between fascicle length and performance may reflect anatomical complexity, limitations in 2 dimension (2D) ultrasonographic tracking, or functional redundancy in untrained populations. Although no significant side-to-side differences were detected, the observed associations suggest that architectural parameters such as muscle thickness and pennation angle may still provide clinically relevant information when interpreting individual performance limitations.

Our findings have clinical and practical implications. The demonstrated architectural symmetry suggests that inter-limb comparisons may not be a reliable metric for detecting early stage dysfunction in untrained individuals. However, the moderate associations between architecture and functional outcomes support the relevance of targeted muscle evaluations especially of the TA and gastrocnemius for understanding performance limitations or guiding rehabilitation strategies. These results also provide normative references for muscle structure function relationships in young adults. Such normative symmetry and association profiles may be particularly useful in establishing expectations for baseline assessments or side-to-side comparisons in rehabilitation and post-injury return to function protocols.

Several limitations must be acknowledged. First, ultrasonographic fascicle tracking is partially subjective and may introduce variability; however, all assessments were performed by a single experienced examiner. In addition, intra-rater and inter-rater reliability coefficients were not calculated in the present study, which should be considered when interpreting the ultrasound-based measurements. Second, the sample consisted of young, recreationally active adults; generalizability to athletic or older populations is limited. In addition, although both male and female participants were included, sex-based analyses were not performed because the sample size was not sufficient for subgroup comparisons. Therefore, potential sex-related differences in muscle architecture and strength should be interpreted with caution. Finally, the lack of 3D motion analysis restricted interpretation of movement strategies during functional tests.

CONCLUSION

This study showed no significant differences between dominant and non-dominant limbs in lower-limb muscle architecture, ankle muscle strength, or static and dynamic functional performance in healthy young adults. However, muscle thickness and pennation angle demonstrated meaningful associations with strength and performance outcomes, suggesting

that these parameters may be more functionally informative than fascicle length. These findings may provide a practical reference framework for side-to-side comparison in clinical assessment and rehabilitation monitoring, particularly in non-athletic young adults. Rather than serving as definitive threshold values, muscle architecture parameters may be used as reference indicators to support the interpretation of functional deficits and recovery processes.

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Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

Idea/Concept: *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Design:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Control/Supervision:*** *Fırat Tan, Hande Güney Deniz;* ***Data Collection and/or Processing:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Analysis and/or Interpretation:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Literature Review:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Writing the Article:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Critical Review:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***References and Fundings:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz;* ***Materials:*** *Fırat Tan, Nazlı Büşra Ciğercioğlu, Ezgi Ünüvar Yüksel, Abdullah Ruhi Soylu, Hande Güney Deniz.*

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