Full length article

Correlation between lower limb isometric strength and muscle structure with normal and challenged gait performance in older adults

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ABSTRACT

Background: Muscular parameters have been considered to influence gait of older adults, but it is still unclear which specific lower limb muscular parameters correlate with kinematics of overground and obstacle crossing in older adults.

Research question: What lower limb muscular parameters correlate and explain kinematics of overground walking and obstacle crossing ability in the elderly?

Methods: Muscle structure was evaluated in 15 older individuals (75.4 ± 5 years) through measures of architecture (muscle thickness, fascicle length, and pennation angle) and muscle quality (echo intensity) from lower limb muscles (vastus lateralis, biceps femoris, rectus femoris, tibialis anterior, and gastrocnemius medialis). Muscle function was assessed through isometric strength of hip, knee and ankle joint muscles. Gait kinematics (toe and heel clearances, step length and gait speed) was evaluated during walking with and without obstacle crossing at preferred and maximal gait speeds. Correlation and regression analyses were performed considering a significance level of 0.05.

Results: Isometric strength did not correlate with gait kinematics and gait speed. Tibialis anterior thickness correlated with lead limb toe clearance, and vastus lateralis thickness with gait speed and step length. Vastus lateralis echo intensity correlated with step length and gait speed.

Significance: Tibialis anterior and vastus lateralis muscles deserve attention in physical training to improve gait of older adults. Specifically, tibialis anterior should receive more attention on exercise programs aiming at improvement of obstacle crossing, and knee extensors when aiming at improving gait speed and step length.

1. Introduction

Locomotion is dependent on the proper functioning of the musculoskeletal system and is a major component of human independence [1]. Muscular losses due to aging may impair mobility and reduce independence [2]. Muscle strength results from a combination of different neuromuscular parameters including muscle architecture [3,4] and muscle quality [5]. While muscle mass is related to muscle thickness [6], the pennation angle relates to the number of in parallel sarcomeres and the fascicle length relates to the serial sarcomeres number [7]. Muscle quality, as measured by the echo intensity (EI), allows the quantity of contractile material in the muscle to be estimated [8]. With aging, there is a reduction in muscle thickness [9,10], pennation angle, fascicle length [11], and a worsening of muscle quality [8], which together lead to a lower muscle strength. To associate these muscular parameters with function, isometric strength is largely evaluated using handheld dynamometers, which are low cost, easy to include in the evaluation routine [12], and have shown good reliability [12,13].

Gait kinematics in the elderly, including the ability to cross obstacles, is known to improve in response to a variety of training regimens [14]. In general, a multicomponent program will promote gains in strength and functional fitness [15] which could have a positive effect on gait kinematics. However, a systematic review found either no or a low association between strength improvements and gait speed without obstacle crossing after training [16]. Previous studies showed that the structure and function of some muscles are related to functional capacity and gait performance in the elderly [5,17,18]. However, it is difficult to rule out contributions from the hip and ankle, since most of the studies addressing the role of muscle strength and architecture in the locomotion of the elderly consider muscles spanning only one joint

(mainly the knee and ankle). In addition, evidence relating to the relationship between muscular parameters and specific gait conditions, such as obstacle crossing which elicits a higher risk of falls in the elderly, is still scarce, and most of the existing studies consider unobstructed gait [4,5,19]. When looking at gait with obstacle crossing, only one previous study investigated the association between the lead limb toe clearance and muscular strength; although this was only assessed during gait initiation [20]. Knowledge of the relationship between muscular parameters (structure, quality, and strength) and gait (with and without obstacles crossing at different speeds) in the elderly might assist health professionals to identify individuals at higher risk of losing independence, and could help in designing more objective intervention programs.

With this goal in mind, we aimed to answer the following question: Which muscular parameters (structural and functional) are correlated, and may explain gait kinematic parameters (toe and heel clearances, step length, and gait speed) during overground gait and obstacle crossing in older adults walking at two gait speeds? Our hypothesis was that elderly individuals with better muscle structure (i.e., larger thickness, pennation angle and fascicle length), better muscle quality (i.e., reduced EI values), and greater muscle strength would show better gait results (higher toe and heel clearances, step length, and gait speed) compared to those with poor muscle structure, quality, and strength. We also expected that the tibialis anterior muscle parameters would be more important in explaining foot clearance, and the knee extensor structure would be better correlated and better explain step length and gait speed.

2. Methods

2.1. Participants

Fifteen community-dwelling older individuals participated in our study (9 women and 6 men; 75.4 ± 5 years; body mass, 68.6 ± 14.8 kg; height, 1.57 ± 0.11 m; BMI, 27.77 ± 4.65 kg/m^2, body fat, 28.9 ± 4.6 %). All participants received a detailed explanation of the study before signing an informed consent form. The local institution ethics committee approved this study (IRB 2.034.508). All procedures followed the Declaration of Helsinki. The study inclusion criteria were as follows: ability to walk independently; no severe auditory, vestibular, visual, and/or neuromusculoskeletal impairments that could prevent them performing one or more tests, not participating in regular physical exercise, and no severe cognitive impairments (the Mini Mental State Examination [21] mean score was 28.2 ± 1.3 and above the 23 cutoff point [21]).

2.2. Study design

This was a cross-sectional study. Data collection was performed on two separate days, with a minimum of 48 h between. On the first day, all participants answered the Mini Mental State Examination and underwent anthropometric measurements (body mass, height, skinfolds, lower limb, thigh and leg lengths, and knee and ankle diameters). Physical tests were divided between participants into two randomized blocks (one for each day). The muscle architecture and muscle echo intensity (EI) of the rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius medialis (GM) and the isometric strength of muscles spanning the hip and ankle joints were evaluated on the first testing day, while the isometric strength of muscles spanning the knee joint and gait evaluations were performed on the second day.

2.3. Muscle architecture and muscle echo intensity (EI)

US techniques to measure muscle architecture and EI are considered to have a good reliability [22–24]. The muscle architecture (thickness,

pennation angle, and fascicle length) and EI of the RF, VL, BF, TA, and GM muscles were measured using B-mode ultrasound (US) equipment (MyLab30 Gold, Esaote Inc., USA), with a linear array probe (60 mm, 7.5 MHz). The US settings were kept constant during all acquisitions (6 cm depth, gain 40, constant focus). The probe was coated with water-soluble transmission gel in order to provide acoustic contact, and was positioned parallel and transverse to the muscle fascicles in the architecture and EI measurements, respectively. Scans were taken using previously utilized locations [22], with the participants lying down and advised to relax. The probe was positioned as follows: for the RF, midway between the anterior superior iliac spine and the proximal end of the patella; for the VL, midway of the line between the greater trochanter and the lateral femoral tuberosity; for the BF, midway of the line between the ischial tuberosity and the tibia lateral condyle; for the GM, proximally at 30% between the lateral malleolus of the fibula and the tibia lateral condyle; and for the TA, proximally at 30% between the fibula lateral malleolus and the tibia lateral condyle [22].

Three images were obtained bilaterally from each muscle by the same investigator, and the mean values from each lower limb were used for subsequent analysis. Images were analyzed with Image J software (National Institute of Health, USA). Muscle thickness was determined as the mean distance between the superficial and deep aponeuroses at five locations [25]. These lines were drawn at right angles between both aponeuroses [25], and were equidistant (one drawn at each extremity, one at the middle, and two between each extremity and the central line of each image). Pennation angle was determined by considering a fascicle showing good resolution and size within the images, and was calculated as the angle between the deep aponeurosis and the fascicle [25]. Fascicle length was determined as the length of the fascicular path between the superficial and deep aponeuroses [25]. When the fascicle length was greater than the probe surface, it was determined through extrapolation using a trigonometric function [26].

EI (also known as muscle quality) was determined by gray scale analysis, and expressed in arbitrary units ranging from 0 (black) to 255 (white). A region of interest was selected to include the highest possible muscle quantity from each image, avoiding the bone and surrounding fascia [5]. In order to eliminate the influence of muscle damage on the EI images, the participants were evaluated without performing vigorous activities before the measurements.

2.4. Maximal isometric strength

The maximal isometric strength was assessed bilaterally using a handheld dynamometer (MicroFET2, Hoggan Health Industries, USA). The handheld dynamometer was chosen due to its wide use in clinical practice evaluation and its reliability [12,13]. Three trials, lasting five seconds each, were performed for each muscular group, and the mean peak value from each lower limb (normalized by body mass) was utilized for analysis. A 90 s rest interval was observed between trials. Participants were verbally instructed and encouraged to perform their maximal effort. Table 1 and Fig. 1 describe and illustrate, respectively, the details of this evaluation.

The strength of the muscles spanning the hip and knee joints was evaluated with the participant on a stretcher, following the procedures described previously (Table 1 and Fig. 1). The dynamometer was firmly attached to a custom-made device built in polyvinyl chloride, similar to that of a previous study [27]. The dynamometer was mounted on one side of the device, and the other extremity, which had a larger basis, was fixed by the examiner to a wall in order to reduce undesired movements. For assessment of the ankle muscle groups, a height-adjustable seat and a custom-made wooden device allowed gradual height adjustment according to the participant's leg length. Evaluations were performed with the participants in a prone position, with arms resting alongside the stretcher, and at seated and supine postures with arms crossed over the chest. The assessment orders of the limb and the muscular groups were randomized for each participant.

Table 1
Testing settings details for the isometric strength assessment.

Muscle group	Position	Dynamometer placement	Belt position
Hip Flex	Supine, knee and hip tested at 90º of flexion [12]	Frontal aspect of the thigh, 5 cm proximal to the patella proximal edge [12]	ASIS and distal third of the non-evaluated thigh
Hip Ext	Supine, non-evaluated limb rested with the knee flexed at 90º, evaluated limb with knee and hip flexed at 90º	Posterior aspect of thigh, 5 cm proximal to the popliteal line	ASIS and distal third of the non-evaluated thigh
Hip Add	Supine, hip tested at neutral position, opposite knee and hip flexed [12]	Medial aspect of the leg, 5 cm proximal to the medial malleolus [12]	ASIS and distal third of the evaluated thigh
Hip Abd	Supine, evaluated lower limb at neutral position [12] and the opposite limb at the same position	Lateral aspect of the leg, 5 cm proximal to the lateral malleolus [12]	ASIS and thighs' distal third
Hip Int Rot	Prone, hip of the evaluated limb at neutral position and knee flexed 90º, opposite limb at neutral position [12]	Lateral aspect of the leg, 5 cm proximal to the lateral malleolus [12]	PSIS and thighs' distal third
Hip Ext Rot	Prone, hip evaluated at neutral position and knee flexed at 90º, opposite limb at neutral position [12]	Medial aspect of the leg, 5 cm proximal to the medial malleolus [12]	PSIS and thighs' distal third
Knee Flex	Sitting, hips and knees flexed at 90º [13]	Posterior aspect of the leg, just proximal to the ankle [13]	Thighs' distal third
Knee Ext	Sitting, hips and knees flexed at 90º [13]	Anterior aspect of the leg, just proximal to the ankle [13]	Thighs' distal third
Ankle Dorsi	Sitting, hips and knees flexed at 90º and ankle at neutral position	Above the dorsal surface of the foot, close to the metatarsal phalangeal joints	None
Ankle Plant	Sitting, hips and knees flexed at 90º and ankle at neutral position	Anterior aspect of the thigh, 5 cm above the upper border of the patella	None

ASIS: anterior superior iliac spines; PSIS: posterior superior iliac spines; Flex: flexors; Ext: extensors; Add: adductors; Abd: abductors; Int Rot: internal rotators; Ext Rot: external rotators; Dorsi: dorsiflexors; Plant: plantar flexors.

2.5. Gait analysis

Gait assessments were performed in four situations as follows: Overground walking at both preferred and maximal speeds, and overground gait with obstacle crossing at both preferred and maximal speeds. The conditions (overground gait and gait with obstacle crossing) were randomized and the trials at a preferred speed were always registered first. At the preferred speed, participants were requested to walk as they do in daily life. At the maximal speed, they were instructed to "walk as fast as you can, safely, not running".

Kinematic data were recorded using 15 infrared cameras (Bonita B10, Vicon Motion Systems, UK) that sampled at 120 Hz. Spherical reflective markers were attached to the participant's body according to the Plug-in Gait Lower Body Modeling [28], with extra markers placed anteriorly (over hallux) and posteriorly (over calcaneus protuberance) at the shoe, and at each superior edge of the obstacle [29]. The sagittal plane 2D kinematic data were analyzed to determine the foot clearance variables. Kinematic data were filtered with a fourth order zero lag Butterworth filter, with a cut-off frequency of 10 Hz, as previously utilized [30], and the mean of both lower limbs was used for analysis.

Participants walked with flat casual shoes, along an 8 m walkway. Three trials were registered for each speed for overground gait, and the gait speed and step length (normalized to the participant's leg length) were determined at each speed.

Ten trials (five with each lower limb as the leading limb) at each speed were registered for obstacle crossing. Participants were not told which limb to use to cross the obstacle first. The obstacle was made of polystyrene (length x width: 80 cm x 20 cm), with height adjusted to 30% of each participant's lower limb length (defined as the distance from the femur's greater trochanter to the ground), and was positioned halfway on the walkway [29]. For both speeds, the lead and trail limb (LL and TL) toe clearance (measured when the hallux was directly above the first obstacle markers), lead limb (LL) heel clearance (measured when the heel was directly above the last obstacle markers), and gait speed were determined.

2.6. Statistical analysis

The sample size was estimated using G*Power (3.1.9.2, Germany) based on a previously determined correlation coefficient between RF, EI, and a gait speed of -0.347 [5], with an alpha level of 0.05 and power of 0.80. Data normality was checked through the Shapiro-Wilk test. Pearson and Spearman's tests were performed to verify the correlation between the muscular parameters (structural and functional) and kinematic gait variables (toe and heel clearances, step length, and gait speed). Correlations were classified [direct (+) or inverse (-)] as weak (0.1–0.35), moderate (0.36–0.67), or strong (0.68–1) [31]. When significant correlations were found, single or stepwise multiple regression analyses were performed in order to investigate which of the muscular parameters could explain the kinematic gait parameters. Single regression analysis was used when a single correlation was observed between muscle and gait variables, whereas multiple regression analysis was used when more than one muscle variable was correlated with gait variables. All tests were performed using SPSS 17.0 (IBM Corp., Armonk, USA), considering a significance level of 0.05.

3. Results

3.1. Overground gait

The preferred gait speed was directly associated with the VL muscle thickness (Table 2), hip external rotation strength, and ankle dorsiflexion strength (Table 3). The multiple regression analysis revealed that only the VL muscle thickness was a significant predictor, explaining 36% of the variance in the preferred gait speed (Table 4). A smaller step length was directly associated with a lower VL quality (Table 2), which was included in the linear regression model (R^2 = 0.27; Table 5).

The maximal gait speed was directly correlated with the VL muscle thickness and the TA pennation angle, and inversely with the TA fascicle length (Table 2). The VL muscle thickness and the TA fascicle length were included in the multiple regression model, and together explained 63% of the variance in maximal gait speed (Table 4). Problems related to multicollinearity were not found, as depicted by the weak correlation between the variables, low values of variance inflation factors, and large tolerance. The step length was inversely correlated with the VL muscle quality, and directly with the RF and VL muscle thickness. The results showed that only the VL muscle quality was a good predictor of step length at maximal gait speed (R^2 = 0.29; Table 4).
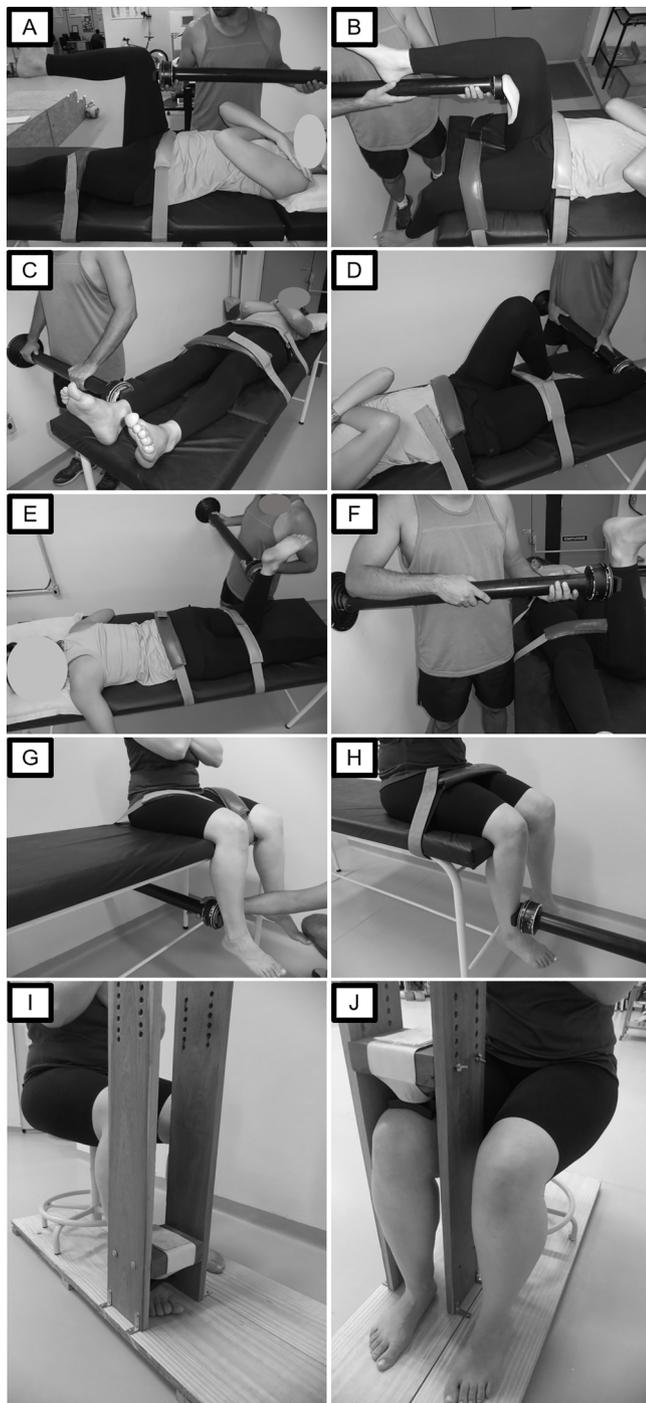
Fig. 1. Illustration of the isometric strength testing settings. A: Hip flexors; B: Hip extensors; C: Hip abductors; D: Hip adductors; E: Hip internal rotators; F: Hip external rotators; G: Knee flexors; H: Knee extensors; I: Ankle dorsiflexors; J: Ankle plantar flexors.

3.2. Obstacle crossing

The preferred gait speed did not correlate with any of the muscular parameters, whereas the leading leg toe clearance showed a direct correlation with the TA muscle thickness and knee flexor strength, with only the TA thickness entering the model ($R^2 = 0.30$; Table 4). An inverse correlation was found between the trail limb toe clearance and the VL pennation angle at the preferred gait speed; this was included in the regression model and explained 32% of the variance in the trail limb toe clearance (Table 5). The heel clearance during gait at the preferred speed showed a direct correlation with the GM quality; this was included in the model and explained 30% of the variance in heel clearance (Table 5).

The maximal gait speed was inversely correlated with the VL muscle quality (Table 2) and explained 26% of the variance in maximal gait speed (Table 5). At maximal gait speed, direct correlations with toe clearance were found for the RF quality and hip adduction strength, as well as for the TA thickness (Table 2) and knee flexor strength (Table 3). The TA thickness ($R^2 = 0.39$) and RF quality ($R^2 = 0.35$) were good predictors of toe clearance, and explained 74% of the variance in the lead limb toe clearance (Table 4). Multicollinearity problems did not occur, as depicted by the low correlation between the variables and the observation of low values of variance inflation factors and large tolerance. There was no correlation between the trail limb toe clearance and muscular parameters. A direct correlation was found between heel clearance and RF quality (Table 2), explaining 50% of the variance in trail limb toe clearance (Table 5).

4. Discussion

In this study, we determined whether muscular parameters (architecture, quality, and strength), from muscles spanning the hip, knee, and ankle joints correlate, and could explain gait kinematics in older adults. To the best of our knowledge, this is one of the first studies to investigate which muscle structure parameters were correlated, and to which extent they explained gait speed, step length, and foot clearances during overground gait, with and without obstacle crossing, in older adults. Our initial hypotheses were that the TA muscle parameters would be more important in explaining the limb clearance during obstacle crossing, whereas the knee extensor parameters would be better correlated and would better explain the step length and gait speed in overground walking. Our main findings partially supported our hypotheses, as they showed that the TA thickness showed moderate correlation with the lead limb toe clearance (~0.55), but not with the trail limb toe clearance. Furthermore, the VL muscle thickness significantly correlated (0.56-0.60) with gait speed in overground walking. Our results suggest that the knee extensor and ankle dorsiflexor muscles should receive attention in training and/or rehabilitation programs aimed at gait improvement in older adults. Furthermore, an ultrasound image assessment of the VL and TA muscles might help to determine the impact of physical training on walking performance.

Isometric strength, which is a common measure in the clinical assessment of older individuals, is related to the quality of life of the elderly [32]; this showed a weak correlation with gait kinematics in the present study, in agreement with previous findings [16]. Considering that daily tasks usually involve concentric and eccentric muscle actions, future studies should test the hypothesis of a stronger relationship with concentric and eccentric forces. It would also be useful to consider that motor control, rather than force, might be important for gait kinematics.

The overground gait at preferred speed was directly and moderately correlated with the VL muscle thickness, hip external rotation, and ankle dorsiflexion strength, whereas the maximal gait speed showed a moderate and direct correlation with the VL thickness and the TA pennation angle, but an indirect correlation with TA fascicle length. These results partially support our initial hypothesis, since structural parameters from the knee extensor muscles showed a good correlation with gait speed. In overground gait speed, the hip and ankle strength parameters were not expected to be as important as the knee extensors. While the knee extensor structural parameters appear to be equally important independent of gait speed, the hip and ankle muscle strengths are more important at a lower speed. However, a fast speed is more dependent on the TA muscle architecture.

The fascicle length is directly related with shortening velocity [3], whereas the fascicle pennation angle is generally associated with hypertrophy (parallel sarcomere increase) [7]. Therefore, one would

Table 2
Correlation coefficients between muscular structural parameters and gait performance during overground and obstacle crossing. Significant correlations are highlighted.

| | Overground gait | | | | Obstacle gait | | | | | | | |
| | Preferred Speed | | Maximal Speed | | Preferred Speed | | | | Maximal Speed | | | |
	Speed	SL	Speed	SL	Speed	LL TC	TL TC	LL HC	Speed	LL TC	TL TC	LL HC
Echo intensity												
Rectus femoris	0.07	−0.004	0.07	−0.05	−0.03	0.47	0.29	0.46	−0.005	0.62*	0.28	0.70**
Vastus lateralis	−0.40	−0.52*	−0.41	−0.54*	−0.46	0.21	0.49	0.50	−0.51*	0.10	0.50	0.40
Biceps femoris	0.17	−0.06	0.15	−0.07	0.02	0.34	0.07	0.27	0.08	0.36	0.07	0.48
Tibialis anterior	−0.40	−0.31	−0.44	−0.36	−0.31	0.11	0.13	0.47	−0.35	−0.03	0.11	0.32
Gastrocnemius med	−0.08	−0.02	−0.13	−0.07	−0.11	0.46	−0.02	0.55*	−0.07	0.45	0.01	0.35
Thickness												
Rectus femoris	0.42	0.48	0.36	0.51*	0.34	0.07	−0.38	−0.25	0.23	0.08	−0.23	−0.21
Vastus lateralis	0.60*	0.48	0.56*	0.53*	0.51	0.17	−0.26	−0.26	0.45	0.20	−0.18	−0.20
Biceps femoris	0.23	0.08	0.28	0.18	0.32	−0.17	−0.22	−0.25	0.33	−0.12	−0.18	−0.23
Tibialis anterior	0.35	0.21	0.34	0.16	0.15	0.55*	0.26	0.17	0.23	0.56*	0.29	0.13
Gastrocnemius med	0.27	0.17	0.36	0.15	0.28	0.005	−0.04	−0.27	0.40	0.02	−0.09	−0.21
Pennation angle												
Rectus femoris	0.03	0.003	0.12	0.18	0.08	−0.30	−0.48	−0.17	0.15	−0.36	−0.45	−0.39
Vastus lateralis	0.08	0.14	0.13	0.25	0.16	−0.18	−0.56*	−0.14	0.20	−0.27	−0.45	−0.34
Tibialis anterior	0.45	0.33	0.52*	0.31	0.32	0.22	0.34	−0.09	0.45	0.35	0.34	0.05
Gastrocnemius med	0.30	0.34	0.41	0.44	0.35	−0.27	−0.29	−0.44	0.35	−0.28	−0.32	−0.44
Fascicle length												
Rectus femoris	0.002	0.16	−0.16	−0.004	−0.02	0.15	0.09	−0.02	−0.22	0.14	0.19	0.06
Vastus lateralis	0.23	0.13	0.08	−0.005	0.14	0.31	0.43	−0.04	−0.02	0.40	0.43	0.21
Tibialis anterior	−0.48	−0.31	−0.54*	−0.36	−0.41	−0.06	−0.41	0.13	−0.33	−0.11	−0.37	−0.02
Gastrocnemius med	−0.31	−0.25	−0.20	−0.27	−0.20	0.11	−0.15	0.20	0.06	0.25	−0.19	0.27

SL: step length; LL TC: lead limb toe clearance; TL TC: trail limb toe clearance; LL HC: lead limb heel clearance; med: medialis.
  * P < 0.05.
  ** P < 0.01.

Table 3
Correlation coefficients between isometric strength and gait performance in overground and obstacle crossing. Significant correlations are highlighted.

| | Overground gait | | | | Obstacle gait | | | | | | | |
| | Preferred Speed | | Maximal Speed | | Preferred Speed | | | | Maximal Speed | | | |
	Speed	SL	Speed	SL	Speed	LL TC	TL TC	LL HC	Speed	LL TC	TL TC	LL HC
Hip Flexion	0.06	0.19	0.02	0.15	0.25	0.05	−0.31	0.02	0.19	0.10	−0.30	0.06
Hip Extension	−0.07	−0.24	−0.15	−0.28	−0.23	0.35	0.13	0.43	−0.25	0.28	0.24	0.14
Hip Abduction	−0.07	0.09	−0.03	0.15	0.12	0.12	−0.21	0.11	0.06	0.10	−0.23	0.10
Hip Adduction	0.31	0.33	0.13	0.20	0.16	0.46	−0.03	0.21	0.01	0.55*	0.12	0.33
Hip Internal Rotation	0.44	0.29	0.24	0.20	0.36	0.20	−0.12	−0.10	0.09	0.10	0.03	−0.09
Hip External Rotation	0.54*	0.42	0.44	0.42	0.40	0.26	−0.16	−0.05	0.23	0.25	0.01	−0.13
Knee Extension	−0.04	−0.03	−0.03	−0.01	−0.06	0.31	−0.11	0.43	0.001	0.18	−0.11	0.15
Knee Flexion	0.41	0.26	0.33	0.22	0.20	0.52*	0.12	0.25	0.16	0.54*	0.21	0.28
Ankle Dorsiflexion	0.58*	0.37	0.48	0.37	0.41	0.48	0.20	0.08	0.23	0.41	0.25	0.01
Ankle Plantar Flexion	0.05	−0.001	0.02	−0.01	0.11	0.20	−0.05	0.17	0.05	0.13	0.03	−0.002

SL: step length; LL TC: lead limb toe clearance; TL TC: trail limb toe clearance; LL HC: lead limb heel clearance.
  * P < 0.05.

Table 4
Multiple linear regression equations.

Independent variable	Regression equation	R	R²	P
Preferred Speed				
Speed (overground)	[(0.571 * VLMT) + 0.125]	0.60	0.36	0.016
Lead limb toe clearance	[(7.239 * TAMT) + 0.278]	0.55	0.30	0.033
Maximal Speed				
Speed (overground)	{[(0.683 * VLMT) + (−0.046 * TAFL)] + 1.045}	0.79	0.63	0.003
Step length	{[(−0.354) * VLEI] + 109.833}	0.54	0.29	0.037
Lead limb toe clearance	{[(7.863 * TAMT) + (0.166 * RFEI)] − 14.748}	0.86	0.74	< 0.001

VLMT: vastus lateralis muscle thickness; TAMT: tibialis anterior muscle thickness; TAFL: tibialis anterior fascicle length; VLEI: vastus lateralis echo intensity; RFEI: rectus femoris echo intensity.

Table 5
Single linear regression equations.

Independent variable	Regression equation	R	R^2	P
Preferred Speed				
Step length	$\{[(-0.300) * VLEI] + 98.156\}$	0.52	0.27	0.047
Trail limb toe clearance	$\{[(-1.706) * VLPA] + 40.705\}$	0.56	0.32	0.028
Lead limb heel clearance	$\{[(0.144) * GMEI] + 0.375\}$	0.55	0.30	0.032
Maximal Speed				
Lead limb heel clearance	$[(0.155 * RFEI) + 1.164]$	0.70	0.50	0.003
Speed (obstacle gait)	$\{[(-0.005) * VLEI] + 1.444\}$	0.51	0.26	0.048

VLEI: vastus lateralis echo intensity; VLPA: vastus lateralis pennation angle; GMEI: gastrocnemius medialis echo intensity; RFEI: rectus femoris echo intensity.

assume that elderly individuals with a longer TA fascicle length and higher fascicle pennation angle should perform better when walking at a faster speed. However, muscle hypertrophy is usually related with fibers of a larger anatomical cross-sectional area that increase the pennation angle, but results in a shorter fascicle length [7]. In our case, elderly individuals with a shorter TA fascicle length and higher pennation angles showed better gait results at fast speed; this suggests that shorter and more pennate dorsiflexors somehow improve gait speed and may influence the ankle muscles reactive activity [33].

The lack of correlation between the VL and GM pennation angles, and the fascicle length with maximal overground gait speed, agrees with a previous study [4]. The quadriceps muscle quality is known to not correlate with the preferred gait speed, although the RF muscle quality has been shown to correlate [5]. The VL thickness is related to both gait speeds, which can be explained by its role for power production during propulsion and in the landing phase, working eccentrically to dissipate impact. From our results and those of previous studies, the VL thickness appears to be an important parameter related to gait speed in the elderly.

The association of gait speed and isometric strength remains controversial in the literature [5,17,34,35]. Our results indicate that the greater the RF and VL thickness, and the better the VL quality, the larger the step length is; however, the isometric strength was not correlated with the step length. Why the parameters relating to muscular architecture show a better relationship with gait parameters remains to be determined.

The kinematics of obstacle crossing is considered to be important in assessing the risk of falls, and is sensitive to the elderly individual's level of physical conditioning [14]. Although the TA muscle thickness and isometric knee flexion strength showed a direct correlation with LL toe clearance, only the TA thickness was a good predictor of LL toe clearance, regardless of gait speed. The TA is an ankle dorsiflexion agonist [36], a joint movement that minimizes the risk for obstacle contact during the gait's swing phase. In a previous study, the ankle dorsiflexors isometric strength was the only lower limb strength measure that predicted the older subjects' fall status [37]. Considering that this musculature has an important role in the assessment of tripping risk, and that the use of a handheld dynamometer for isometric strength assessment is an inexpensive, easy to perform [12], and has good reliability [12,13], we suggest the inclusion of dorsiflexor isometric strength assessment in elderly evaluation routines. Such a suggestion is endorsed by a recent report showing the importance of ankle muscle reactive activity in the elderly during perturbed gait [33].

In this regard, a previous study showed that the LL toe clearance during gait initiation was not related to lower limb dynamic strength in older women [20]. The authors observed that the elderly utilized a strategy that moved the toe backward, away from the obstacle, crossing it at higher vertical distance, compared to younger subjects, who moved the toe straight up [20]. This pattern could be related to the TA weakness changing the movement pattern during obstacle crossing. However, apparently this was not the case, since the authors reported

no correlation between the dynamic strength and vertical clearance [20].

When obstacle crossing was performed at maximal gait speed, the hip adduction strength (in addition to knee flexion) also presented significant correlation with LL toe clearance. This could be related to the strategy utilized for positioning the foot before crossing, which is associated with the vertical distance achieved, and alters the angular pattern of joint motion during crossing [38]; this may also result from searching for better hip stability during the task. The association between the vertical clearance and the RF and GM echo intensities were unexpected and require further investigation.

Our study has some limitations. First, we did not consider a fixed speed for gait assessment, as we considered that a fixed speed could elicit adaptations for some participants. In order to minimize this limitation, we opted for the maximal speed in addition to the preferred speed. In addition, due to our relatively small sample size, the results should be viewed with caution when applying them to the general elderly population. Muscle EI evaluated by US was related to muscle attenuation assessed by computer tomography [39]. Muscle attenuation is an indicative of fat infiltration [40]. One of the EI limitations is that it can partially reflect fat infiltration and is affected by muscle thickness, as US waves are attenuated as they move deeper into the body tissues [41]. Finally, we evaluated the isometric strength using a handheld dynamometer, which, despite the validity shown in previous studies, may present some limitations. However, we chose this technique since it has larger application in the clinical field. Further studies should consider strength measures for the full joints' range of motion, which is perhaps a more physiological and functional way of obtaining muscle strength that might be better correlated with gait, assumed to be related with functionality.

5. Conclusions

We suggest that the TA and VL muscle structure (mainly muscle quality and thickness) plays an important role in older adults' gait kinematics, and may have important implications in reducing the risk of trips during obstacle crossing. Therefore, these muscular parameters should receive more attention when the goal is to maintain or improve the older adults' independence.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the

online version, at doi: https://doi.org/10.1016/j.gaitpost.2019.07.131.

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