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Relationship between the architecture and function of ankle plantar flexors with Achilles tendon morphology in ballet dancers

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ABSTRACT

Achilles tendinopathy is the most frequent foot overuse injury in ballet dancers and knowledge of clinically modifiable factors related to tendon structure in a population at risk, such as ballet dancers, would be important for the development of preventive programs. Therefore, the present study aimed to assess relationships of gastrocnemius muscle architecture and ankle plantar flexors function with Achilles tendon morphology in ballet dancers. Fifty-four measures from 27 ballet dancers were collected. Tendon morphology (thickness, echogenicity, hypoechoic areas and neovascularisation) and muscle architecture (thickness, pennation angle and fascicle length) were evaluated using ultrasonography; ankle plantar flexors torque was evaluated using hand-held dynamometry, flexibility was evaluated in maximal weight-bearing ankle dorsiflexion position using inclinometer, and endurance was evaluated using the heel rise test. Ankle plantar flexors torque and medial gastrocnemius muscle architecture (thickness, pennation angle and fascicle length) are associated with Achilles tendon thickness in ballet dancers ($r^2 = 0.24$, $p = 0.008$). Ankle plantar flexors torque and medial gastrocnemius muscle fascicle length are also associated with the echogenicity of the Achilles tendon ($r^2 = 0.13$, $p = 0.03$). These findings call attention to the potential importance of ankle plantar flexors muscle force in healthy ballet dancers for the prevention of alterations in Achilles tendon structure.

1. Introduction

The practice of ballet involves repetitive movements, often in unphysiological positions, creating high loads and strain on muscles and ligaments, which may result in injuries (Nilsson, Leanderson, Wykman, & Strender, 2001; Silbernagel, Thomeé, Thomeé, & Karlsson, 2001). Musculoskeletal injuries are common in ballet dancers, with lower extremity overuse injuries being the most common in this population (Nilsson et al., 2001; Sobrino, de la Cuadra, & Guillén, 2015). Achilles tendinopathy (AT) have been shown to be the most frequent foot overuse injury in ballet dancers (Sobrino et al., 2015), where AT accounts for 19% of the sustained injuries (Smith et al., 2016). In ballet, in addition to repeated jumps (Smith et al., 2015), the *pointé* work, in which dancers maintain maximum weight-bearing plantar flexion of the ankle, may increase tendon overload and be one of the causes for the high incidence of AT in ballet.

AT is diagnosed by clinical and imaging examinations (Alfredson & Cook, 2007). Affected tendons normally exhibit hypoechoic regions, neovessels and tendon thickening (Alfredson & Cook, 2007). However, although the presence of these changes is one of the

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criteria for the diagnosis of tendinopathy, they are frequently found in asymptomatic athletes (Alfredson & Cook, 2007; Comin et al., 2013). A recent systematic review with meta-analysis has shown that, when there are ultrasound tendon abnormalities in asymptomatic individuals, they are seven times more likely to develop AT (McAuliffe, McCreesh, Culloty, Purtill, & O'Sullivan, 2016).

In addition to morphological alterations, reduced ankle dorsiflexion (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999; Mahieu, Witvrouw, Stevens, Van Tiggelen, & Roget, 2006; Rabin, Kozol, & Finestone, 2014) and weak ankle plantar flexor muscles (Mahieu et al., 2006) have also been shown to be risk factors for AT. In this context, strengthening and stretching the ankle plantar flexors are frequently recommended for treatment and prevention of AT (Alfredson & Lorentzon, 2000; Carcia, Martin, Houck, Wukich, 2010; McCrory et al., 1999). However, not much is known about the exact mechanism by which exercise or sports participation affect the Achilles tendon.

A decrease in triceps surae muscle pennation angle has been recently observed in individuals with AT in comparison to healthy controls (Romero-Morales et al., 2019). It has also been shown that decreases in the pennation angle of the triceps surae muscle fibers, caused by inadequate loading, can influence Achilles tendon curvature (Kinugasa, Yamamura, Sinha, & Takagi, 2016). This decrease in the triceps surae muscle fibers pennation angle determines changes in force output consequent to modifications in intramuscular fiber orientation, potentially providing a mechanism for Achilles tendon overload (Kinugasa et al., 2016). However, to our knowledge, the relationship between the function and architecture of the triceps surae muscles and Achilles tendon morphology in dancers remains unknown.

Recently, medial gastrocnemius muscle thickness, fascicle length and pennation angle, as well as Achilles tendon cross-sectional area (CSA), have been shown to be associated with running performance in sprinters (Monte & Zamparo, 2019). Furthermore, runners submitted to eccentric training increased the Achilles tendon CSA and the gastrocnemius muscle pennation angle (Sanz-López, Berzosa Sánchez, Hita-Contreras, Cruz-Diaz, & Martínez-Amat, 2016). Compared to young individuals, the elderly exhibit less ankle plantar flexor force, smaller CSA and lower gastrocnemius muscle pennation angle, in addition to a higher CSA in the Achilles tendon (Stenroth, Peltonen, Cronin, Sipilä, & Finni, 2012). Although these studies suggested that there is a relationship between ankle plantar flexor muscles function and architecture and Achilles tendon morphology, it is unknown whether this relationship exists or which factors can explain Achilles tendon structure.

Dancers have also been recently shown to have decreased ankle plantar flexors endurance than non-dancer (Zellers, van Ostrand, & Silbernagel, 2017). However, the relationship between ankle plantar flexors endurance and tendon structure remains obscure. Knowledge of clinically modifiable factors related to tendon structure in a population at risk of developing AT, such as ballet dancers, would be important for the development of preventive programs. Overuse injuries to the tendons are associated with long periods of sick leave and can lead dancers to end their careers prematurely (Nilsson et al., 2001). These aspects highlight the importance of studies involving tendon morphology in ballet dancers. This is especially relevant considering the lack of evidence regarding preventive programs for AT (Peters, Zwerver, Diercks, Elferink-Gemser, & van den Akker-Scheek, 2016). Therefore, the present study aimed to assess whether there is a relationship between Achilles tendon morphology, gastrocnemius muscle architecture and ankle plantar flexors function (strength, flexibility and endurance) in ballet dancers.

2. Methods

2.1. Participants

Twenty-seven ballet dancers of both sexes, aged between 15 and 35 years, had both lower limbs assessed (n = 54 measures). Considering an effect size of 0.5, alpha of 0.05, power of 0.95 and six outcomes included in the regression model, a minimum of 49 measures are required according to a sampling calculation performed using G*Power software (version 3.1). Inclusion criteria were: dancers regularly engaged in ballet (at least once a week, for at least one year) experienced in the *pointé* work, who exhibited no musculoskeletal injury in the last six months, no history of lower limb surgery or any vestibular, neurological or musculoskeletal alteration that interfered or contraindicated the procedures of this study. Participant recruitment was conducted by advertising the project in dance schools in the city, the university and on social media. The present study was approved by the Research Ethics Committee of the Federal University of São Carlos (protocol number 58262116.1.0000.5504), and all participants gave their informed consent. For participants younger than 18 years of age, consent was also obtained from their parents/legal guardians.

2.2. Procedures

Participants were assessed with respect to medial gastrocnemius muscle architecture and Achilles tendon morphology, followed by ankle plantar flexors torque, flexibility and endurance. Both lower limbs of all participants were assessed in a random order. Subjects were asked not to engage in any non-habitual physical activity for 24 h before the tests and to use clothes suitable for physical activities during the tests.

In order to test the reliability of the outcomes, 10 measures were assessed in a pilot test-retest study separated by 48 to 72 h by the same assessor and the intraclass correlation coefficient ($ICC_{3,1}$) and standard error of measurement (SEM) were calculated. ICCs ranged from 0.76 to 0.97, indicating good to excellent reliability (Table 1).

Table 1
Achilles tendon morphology, medial gastrocnemius muscle architecture and ankle plantar flexors function in the study sample including the reliability of the measurements.

Variables	Mean (SD)	$ICC_{3,1}$ (SEM)
Tendon thickness (cm)	0.41 (0.05)	0.94 (0.01)
Tendon echointensity (0 to 255)	76.9 (11.8)	0.85 (3.2)
Muscle thickness (cm)	1.86 (0.30)	0.86 (0.07)
Pennation angle (degrees)	20.8 (3.0)	0.78 (1.1)
Fascicle length (cm)	5.35 (1.11)	0.76 (0.24)
Ankle plantar flexor torque (Nm)	98.1 (25.2)	0.97 (5.7)
Ankle dorsiflexion flexibility (degrees)	44.8 (6.5)	0.80 (2.2)
Ankle plantar flexors endurance (repetitions)	29 (17)	0.89 (2)

$ICC_{3,1}$: intra-rater reliability; SEM: standard error of measurement.

2.3. Assessments

2.3.1. Ultrasonography

A Venue 40 ultrasound (GE Health Care, Buckinghamshire, UK) with a 12L-SC linear transducer and frequency of 7.5 ± 20% MHz was used for morphological assessments of tendon and muscle architecture; the region of interest was at a depth of 2–4 cm. The participants were placed in prone lying, with the knee extended and the hip in neutral rotation. The feet were positioned outside of the examining table and in contact with a wall in order to maintain their ankles in a neutral position (90°) (Simpson, Kim, Bourcet, Jones, & Jakobi, 2017).

2.3.1.1. Achilles tendon morphology. Achilles tendon morphology was assessed in the proximal, medial and distal portions of the tendon (Comin et al., 2013; Jhingan et al., 2011). Three images were obtained from each portion and the average among all measures in each limb was used in analyses. The presence of hypoechoic areas and neovascularization was also verified (Comin et al., 2013; Jhingan et al., 2011):

- *Achilles tendon thickness:* tendon thickness was measured using ImageJ software (National Institutes of Health, Bethesda, MD) (Comin et al., 2013; Jhingan et al., 2011). For the distal portion, tendon thickness was measured at 1 cm from insertion (Fig. 1A); for the medial portion, tendon thickness was measured at the middle of the image (Fig. 1B); and for the proximal portion, tendon thickness was measured at 1 cm from the origin of the tendon (Fig. 1C). The origin was defined as the insertion site of the last soleus muscle fibers and insertion at the most proximal point of attachment to the calcaneus (Jhingan et al., 2011).
- *Achilles tendon echogenicity:* tendon echogenicity was measured using the standard histogram function for grayscale images of Adobe Photoshop Elements Software (version 13, Adobe Systems Inc., San Jose, CA, USA). This function expresses values between 0 and 255, where the lower the value, the darker the image, indicating greater structural change in the tendon (Malliaras, Purdam, Maffulli, & Cook, 2010; Suydam & Buchanan, 2014).

2.3.1.2. Gastrocnemius muscle architecture. Medial gastrocnemius muscle architecture was evaluated in the proximal third of the leg (between the interarticular line of the knee and the lateral malleolus), at the midpoint between the medial and lateral edges of medial gastrocnemius muscle (Abe, Kumagai, & Brechue, 2000; König, Cassel, Intziegianni, & Mayer, 2014; Legerlotz, Smith, & Hing, 2010). Three images of the medial gastrocnemius muscle were collected and the averages of the measures were used in analyses:

- *Medial gastrocnemius muscle thickness*: the linear distance between the deep and superficial aponeuroses was measured using the ImageJ software (Legerlotz et al., 2010) (Fig. 2).
- *Medial gastrocnemius muscle pennation angle*: the pennation angle was measured as the angle between the deep aponeurosis and the echoes of the interspaces between the fiber bundles (following the fibers orientation), using the ImageJ software (Legerlotz et al., 2010) (Fig. 2).
- *Medial gastrocnemius muscle fascicle length*: fascicle length was obtained by trigonometry. Muscle thickness was divided by the sine of the pennation angle in each image, as previously described (Legerlotz et al., 2010).

2.3.2. Muscle torque

A handheld dynamometer was used to assess isometric ankle plantar flexors torque (Lafayette Instruments, Lafayette IN, USA). Participants were placed in prone lying with their feet outside the examining table and inelastic bands were used to stabilize the subjects and the dynamometer (Supplementary material 1A). The dynamometer was placed in the plantar aspect of the metatarsophalangeal joints (Scattone Silva et al., 2016). Participants were instructed to use the maximum possible force against the device. One repetition was performed with each limb for familiarization purposes, followed by three valid repetitions on each limb. Each contraction was held for five seconds with a one-minute interval between them. To calculate torque, the value obtained in Newtons was multiplied by the ankle joint effective lever-arm (distance between the posterior aspect of the calcaneus and the first metatarsophalangeal joint) (Scattone Silva et al., 2016). The average of the three measures was used in analyses.

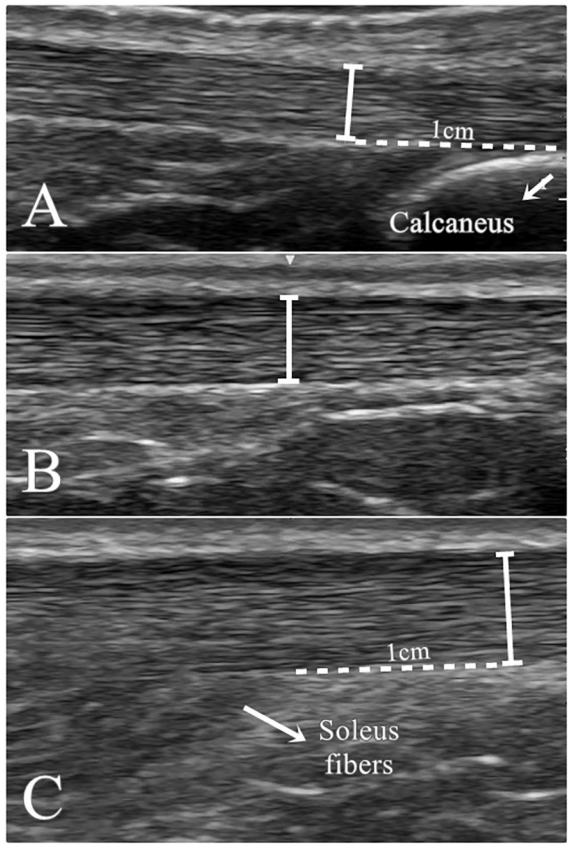

Fig. 1. Achilles tendon thickness measurement. A – Distal portion, B – Medial portion, and C – Proximal portion.

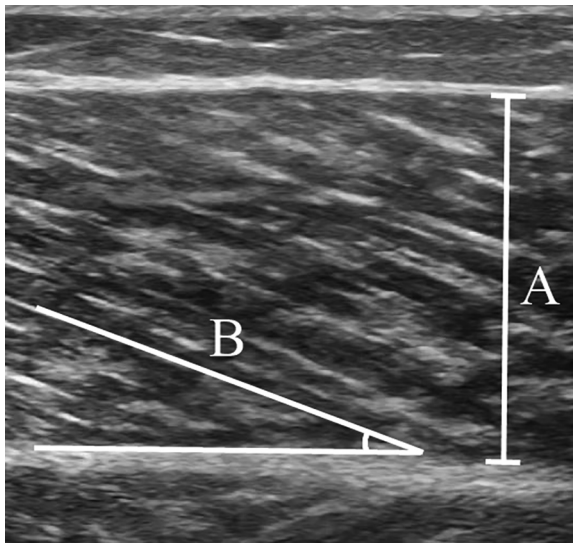

Fig. 2. Measurement of medial gastrocnemius muscle thickness (A) and pennation angle (B).

2.3.3. Flexibility

For the assessment of ankle plantar flexors flexibility, the maximal weight-bearing ankle dorsiflexion angle was measured with an inclinometer (Scattone Silva et al., 2016). Participants stood barefoot in the lunge position in front of a wall. They were instructed to lunge, until the posteriorly located limb reached maximum dorsiflexion, without losing contact between the heel and the floor and maintaining the knee extended (Supplementary material 1B). The subtalar joint position was controlled by maintaining the foot

aligned with a line taped on the floor (Barton, Bonanno, Levinger, & Menz, 2010). In the maximum dorsiflexion position, the inclinometer was placed on the anteromedial surface of the tibia, 10 cm distal to the tibial tuberosity (Scattone Silva et al., 2016). Three measures were taken on each limb and the highest value for each limb was used in analyses.

2.3.4. Muscle endurance

The heel rise test was used to assess ankle plantar flexors muscle endurance (Sman et al., 2014). This test employed a platform with two vertical rods and an elastic band tied to them, in a horizontal position (Sman et al., 2014). The height of the platform can be adjusted so that the elastic band is placed immediately below the participant's calcaneus in maximal plantar flexion during the test. Participants were positioned on this platform in single-leg stance in front of a wall. They were allowed to touch the wall with the fingertips of one of their hands for balance. Initially, participants were instructed to rise up on their toes, performing maximal ankle plantar flexion and holding this position so that the elastic band could be adjusted just clear of their heel (Supplementary material 1C) (Sman et al., 2014). After a one-minute rest, in single-leg stance, participants performed plantar flexion movements (heel rises) at 46 beats per minute, controlled by a metronome (Sman et al., 2014). On the first beat, participants performed their maximum heel rise, clearing the elastic band, and on the second, they returned to the initial position with their foot in total contact with the platform. Participants performed heel rises in this manner until the following occurred in two consecutive occasions: a) not reaching maximum plantar flexion controlled by the elastic band, b) excessive leaning on the wall with obvious trunk flexion, c) bending the knee during the movement, d) losing the rhythm established by the metronome; or abandoning the test (Sman et al., 2014). The test was conducted once on each limb and the number of maximum heel rise repetitions was used in analyses.

2.4. Statistical analysis

The dependent variables were Achilles tendon thickness and echogenicity. Given that no tendon exhibited hypoechoic areas and neovascularization, no model was tested to verify the association using these variables. The independent variables were ankle plantar flexors isometric torque, flexibility and endurance, medial gastrocnemius muscle thickness, pennation angle and fascicle length. The independent variables were included in a model for each dependent variable in order to determine their explanatory power using backward multiple linear regressions. The criterion for the variable to remain in the model was $p < 0.05$ and, to be removed, $p > 0.1$. Analyses were conducted using SPSS version 17.

3. Results

Twenty-five females and two males were assessed (22 ± 5 years of age, 57 ± 11 kg of body mass, 1.6 ± 0.1 m of height). The mean ballet practice time of the participants was 10 ± 8 years. Descriptive results regarding tendon morphology, muscle architecture and ankle plantar flexors function of the participants are presented in Table 1.

After the regression analysis, thickness, pennation angle and fascicle length of the medial gastrocnemius, and ankle plantar flexor torque remained in the final model of association with Achilles tendon thickness ($F_{4.49} = 3.93$, $p = 0.008$). This model explained 24% of thickness variance in the Achilles tendon ($r^2 = 0.24$). Ankle plantar flexors torque and gastrocnemius thickness were significantly related to tendon thickness (Table 2).

Ankle plantar flexor torque and length of the medial gastrocnemius fascicle remained in the final model as variables associated with echogenicity of the Achilles tendon ($F_{2.51} = 3.71$, $p = 0.03$). This model explained 13% of the variance in echogenicity of the Achilles tendon ($r^2 = 0.13$). Ankle plantar flexor torque displayed a significant relationship with tendon echogenicity (Table 2).

4. Discussion

The results of the present study demonstrated that medial gastrocnemius muscle architecture measures and ankle plantar flexors torque are associated with the morphology of the Achilles tendon in young ballet dancers. More specifically, the variance in Achilles

Table 2
Final model results of the multiple linear regressions to identify variables associated with Achilles tendon thickness and echointensity.

	Unstandardized coefficient (SE)	Standardized coefficient	P value
Achilles tendon thickness			
Constant	0.08 (0.16)	–	0.63
Muscle thickness	−0.17 (0.08)	−1.08	0.04*
Pennation angle	0.01 (0.01)	0.83	0.07
Fascicle length	0.05 (0.03)	1.26	0.06
Torque	0.001 (0.0)	0.39	0.01*
Achilles tendon echointensity			
Constant	77.8 (8.6)	–	< 0.01*
Fascicle length	2.68 (1.45)	0.25	0.07
Torque	−0.16 (0.06)	−0.33	0.02*

*Significant correlation. SE: standard error.

tendon thickness is associated with the ankle plantar flexors torque, muscle thickness, pennation angle and length of the medial gastrocnemius muscle fascicle. Some of the echogenicity variance of the Achilles tendon is also associated with the ankle plantar flexors torque and the medial gastrocnemius muscle fascicle length. These findings indicate that there is a relationship between ankle plantar flexion function and morphology and Achilles tendon structure, and that these factors should be considered when aspects of Achilles tendon morphology are involved.

Muscle force is directly related to muscle architecture, with changes in force being shown to be related to changes in muscle architecture (Folland & Williams, 2007; Lieber & Fridén, 2000). The combination of plantar flexion torque and gastrocnemius muscle architecture as factors associated with Achilles tendon morphology in the present study reinforces the importance of the ankle plantar flexors in Achilles tendon structure. Given these results, it can be speculated that ankle plantar flexor muscle strengthening exercises might be important for the treatment and/or prevention of Achilles tendon disorders in ballet dancers. However, clinical trials are needed to verify the effectiveness of ankle plantar flexors strengthening in decreasing the incidence of AT in at-risk populations. In light of the existing evidence, considering that the link between these variables and AT is unwarranted, it cannot be confirmed that an increase in plantar flexion force is a protective factor for the Achilles tendon.

An increase in the Achilles tendon CSA is expected in some stages of AT, due to structural alterations caused by the injury and repair process (Alfredson & Cook, 2007; Cook & Purdam, 2009). It is also suggested that greater Achilles tendon thickness is a risk factor for AT in athletes (Jhingan et al., 2011). Conversely, a previous study found that healthy runners exhibited thicker Achilles tendons compared to sedentary individuals (Ying et al., 2003). Increased tendon thickness in athletes of certain sports may occur due to structural tendon adaptation secondary to sport-specific loading (Cassel et al., 2016). How much of tendon thickness may be accountable to a change in the tendon material properties is a subject of debate (Cassel et al., 2016). It is possible that tendon structural changes are a determining factor when considering whether more or less tendon thickness is beneficial. For ballet dancers with no morphological changes in the tendon, the association between strong ankle plantar flexors and a thicker Achilles tendon may decrease the risk of AT, but more studies are necessary to test this hypothesis.

Since the architecture of the medial gastrocnemius muscle and the Achilles tendon are part of the same musculotendinous structure, a higher percentage of association in the multiple regressions was expected, since the model included both factors. This result may be due to the fact that we only assessed one component of the triceps surae, which may be a limitation of the present study. A study with cadavers showed that the musculotendinous units of the triceps surae muscles have a complex organization and load distribution in the Achilles tendon may not be uniform (Toumi et al., 2016). Thus, the load imposed on the Achilles tendon would be subject to the anatomical influences of the corresponding muscle group, making the contribution of plantar flexor components in the tendon variable (Toumi et al., 2016). Given that there may not be linearity in tendon behavior in the face of the loads applied by each triceps surae component, it can be assumed that the most important loads are those imposed on the tendon as a whole, which may explain why force was one of the factors present in the two models. When a tendon is under repetitive mechanical stress, greater than its capacity to repair and remodel, it may not be able to continue supporting the imposed load, and microscopic changes start to occur (Alfredson & Cook, 2007; Cook & Purdam, 2009). Structural changes in the tendon and less organization and heterogeneity in the tendon's microstructure (lower echogenicity) are seen in overloaded tendons (Alfredson & Cook, 2007; Chimenti et al., 2014; Cook & Purdam, 2009). Thus, addressing the tendon load-bearing capacity (i.e. increase muscle force) may be more important than other components such as muscle architecture. Ankle plantar flexors flexibility and endurance are less likely to be relevant in this scenario, since these variables showed no association with tendon structure. Regarding the endurance test, since we did not include electromyographic evaluations during the task, we are unable to determine which kind of fatigue occurred in our test. Future studies should also verify the effects of muscle activation and fatigue in tendon structure.

Although the present study has found interesting results, a number of limitations should be acknowledged. Only experienced asymptomatic dancers, with no morphological changes in the tendon, were assessed and the same relationships may not be present in other populations. As stated earlier, the assessment of only one component of the triceps surae muscle does not fully elucidate the relationship between Achilles tendon and triceps surae architecture. Previous studies usually measured only one part of the gastrocnemius and extrapolated the results to the triceps surae as a whole (Kuyumcu et al., 2016; Pamukoff & Blackburn, 2015). However, to determine the relationship between triceps surae architecture and Achilles tendon structure, evaluating only one part may not be sufficient. Another limitation of this study is the fact that the anatomical lever-arm of the triceps surae was not measured. With the anatomical lever-arm and the effective lever-arm data, the effective mechanical advantage of the triceps surae can be calculated, which is a variable of direct relevance to functional load of the Achilles tendon (Biewener, Farley, Roberts, & Temaner, 2004). Future studies should address this issue and determine the degree of interdependence between changes in ankle plantar flexor force and architecture and changes in tendon morphology. Future research should also investigate the potential preventive effect of ankle plantar flexors strengthening programs for reducing the incidence of AT in at-risk populations, such as dancers.

5. Conclusion

The results of the present study show that the torque of ankle plantar flexors and medial gastrocnemius muscle architecture (thickness, pennation angle and fascicle length) are associated with Achilles tendon thickness in ballet dancers. Ankle plantar flexors torque and medial gastrocnemius muscle fascicle length are also associated with the echogenicity of the Achilles tendon in this population. These findings call attention to the potential importance of ankle plantar flexors muscle force in healthy ballet dancers for the prevention of alterations in Achilles tendon structure.

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Declaration of Competing Interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.102494.

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