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Foot muscle morphology is related to center of pressure sway and control mechanisms during single-leg standing

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Conflict of Interest Statement

The authors declare that there are no known conflicts of interest related to this project that could have influenced this manuscript.

Highlights:

- 1. Larger abductor hallucis is related to smaller COP sway.
- 2. Abductor hallucis affects open-loop and closed-loop control mechanisms.
- 3. Larger peroneus muscles are related to larger COP sway.
- 4. Training intrinsic foot muscles may benefit balance.

Abstract:

Maintaining balance is vitally important in everyday life. Investigating the effects of individual foot muscle morphology on balance may provide insights into neuromuscular balance control mechanisms. This study aimed to examine the correlation between the morphology of foot muscles and balance performance during single-leg standing. Twenty-eight recreational runners were recruited in this study. An ultrasound device was used to measure the thickness and cross-sectional area of three intrinsic foot muscles (abductor hallucis, flexor digitorum brevis and quadratus plantae) and peroneus muscles. Participants were required to perform 30 seconds of single-leg standing for three trials on a force plate, which was used to record the center of pressure (COP). The standard deviation of the amplitude and ellipse area of the COP were calculated. In addition, stabilogram diffusion analysis (SDA) was performed on COP data. Pearson correlation coefficients were computed to examine the correlation between foot muscle morphology and traditional COP parameters as well as with SDA parameters. Our results showed that larger abductor hallucis correlated to smaller COP sway, while larger peroneus muscles correlated to larger COP sway during single-leg standing. Larger abductor hallucis also benefited open-loop dynamic stability, as well as supported a more efficient transfer from open-loop to closed loop control mechanisms. These results suggest that the morphology of foot muscles plays an important role in balance performance, and that strengthening the intrinsic foot muscles may be an effective way to improve balance.

Keywords: abductor hallucis; peroneus muscles; Stabilogram diffusion analysis; open-loop control; closed-loop control

1. Introduction

Balance control ability is vital to everyday life and a lack of balance control could lead to falls or musculoskeletal disorders such as an ankle sprain [1, 2]. To assess balance performance, postural sway during single-leg standing conditions is often used in literature [3, 4]. The foot, as the only part of the body that contacts the ground during single-leg standing, needs to be sufficiently stable to maintain the center of mass within the base of support.

As force generators, foot muscles (including extrinsic and intrinsic foot muscles) contribute to stability and balance control. Extrinsic foot muscles have been shown to play an important role in single-leg standing balance [4, 5]. Fatiguing of these muscles causes increased postural sway during balance tests [5]. Among these extrinsic foot muscles, peroneus muscles (PER) contribute to lateral ankle stability [6] and training these muscles is suggested to prevent ankle sprain. Some researchers have also suggested that intrinsic foot muscles, which originate and insert in the foot, may also play a role in balance control [7] by stabilizing the foot during single-leg standing and locomotion [8, 9]. For example, the abductor hallucis (AbH) and flexor digitorum brevis (FDB) help support the medial longitudinal arch [10]. Moreover, a strong AbH could stiffen the foot [11], and thus make it a more stable structure for weight bearing and balance control. Recently, the “foot core system” paradigm has been introduced, which considers the intrinsic foot muscles as “local stabilizers” and extrinsic foot muscles as “global movers” [7]. The foot core paradigm suggests that intrinsic foot muscles contract to stabilize the foot during static and dynamic activities. There are, however, few experimental studies to support this concept due to the small size and location of intrinsic foot muscles.

Studies using intramuscular electromyography (EMG) suggest that increasing postural demand by changing from double-leg standing to single-leg standing increases the activity in three plantar intrinsic foot muscles, namely AbH, FDB and quadratus plantae (QP) [8]. However, using intramuscular EMG has limited applications due to its invasive nature. In addition, toe strength has previously been correlated with balance [12], suggesting that increased strength of the toe plantar flexor muscles may have some value in decreasing fall risk in older people. However, the toe plantar flexors include both extrinsic and intrinsic foot muscles. Therefore, discerning whether these intrinsic foot muscles play an important role in balance control may require alternative non-invasive investigation techniques.

Currently the only non-invasive way to examine the role of specific muscles is by using an indirect measure of muscle strength, e.g. muscle morphology. Examining both intrinsic and extrinsic muscle morphologies could provide further insights into the roles of these muscles in balance control. Ultrasound measurements have been shown to be both valid and reliable for assessing intrinsic and extrinsic foot musculature [13, 14]. Knowing how individual muscle morphology contributes to balance performance could provide further evidence-based insights into which muscles have functional qualities [7] that would benefit training or treatment strategies. To the authors' knowledge, there is no study available that has examined the relationship between foot muscle morphology and balance performance.

Traditional measurements of center of pressure (COP), e.g. amplitude and ellipse area, have been used as postural sway indicators during standing [3]. Larger values of these parameters indicate decreased stability and have been linked to increased risk of falling [15]. In addition to traditional COP measures, stabilogram diffusion analysis (SDA) has been introduced as a method that enables COP trajectories to be modeled as fractional Brownian motion, whereby two neuromuscular control systems can be disentangled into two operations: open-loop control operating without sensory feedback, and closed-loop control operating with sensory feedback. Thus, SDA can provide deeper and more specific insights into postural control strategies, revealing dynamic and stochastic characteristics of the COP. Indeed, several SDA parameters such as diffusion coefficients, critical times, and critical displacements have been termed "physiologically meaningful" and have shown sensitivity to impaired balance [16], ageing

[17], ultra-marathon fatigue [18], and plantar flexor muscle fatigue [19]. Results achieved from SDA are therefore of particular interest, as certain intrinsic or extrinsic foot muscles may play specific roles in postural control, from either a directional (anterior-posterior versus medial-lateral) or control mechanism (open- versus closed-loop) perspective. Understanding these roles may reveal much needed links between balance and lower-limb neuromuscular control.

Therefore, this study aimed to examine the association between the foot muscles' morphology, including three intrinsic foot muscles (AbH, FDB and QP) and one extrinsic foot muscle (PER), with COP variables during single-leg standing in healthy and physically active individuals. Muscle morphology as well as balance strategies can be affected by particular sporting type. As running is a very popular activity, we selected a homogenous group of recreational runners for this study. EMG studies have shown that these muscles have an important role in balance control [6, 8], and thus we hypothesized that larger morphology of the selected foot muscles would be associated with smaller COP displacement, especially in the medial-lateral direction. We further expected that foot muscle morphology might also play a role in balance control strategies. Thus, our secondary hypothesis was that foot muscles (that are found to influence COP sway) also influence postural control mechanisms. Specifically, we expected that participants with larger intrinsic foot muscles would exhibit less short-term instabilities (smaller short-term diffusion coefficients). The results of this study might provide insights into understanding how foot muscles contribute to balance control. Both athletic trainers and the elderly could benefit from a better understanding of the association between muscle morphology and balance performance.

2. Methods

2.1. Participants

Thirty-one young, physically active volunteers (13 females and 18 males) participated in this study. Ethics approval was granted by the Medical Ethics Committee of KU Leuven and written consent was obtained from each participant. All participants were recreational runners who ran at least 15 km per week and were injury-free in their lower limbs for the 6 months prior to testing. Some studies show that foot posture affects balance performance [20, 21], and thus foot posture was assessed using the 6-item Foot Posture Index (FPI). Foot type was classified as a pronated posture with a FPI score greater than or equal to +6, a normal posture with a score from 0 to +5, or a supinated posture with a score less than or equal to -1 [22].

2.2. Equipment and procedure

For single-leg standing measurements, the participants were required to stand on their right foot with their eyes open and focused on a cross mark placed at eye level approximately 5 m in front of them. Participants' arms were held crossed on the chest. Ground reaction forces were recorded with a force plate (sampling frequency of 900Hz, AMTI, Watertown, US). A longitudinal line was placed on the force plate to control foot position [20] by aligning the weight-bearing foot on the line so that it bisected the calcaneus and the second and third metatarsals. Participants stood as still as possible on their right foot for 30 seconds. Prior to testing, participants were allowed practice trials to familiarize themselves with the procedure. Subsequently, three successful trials were recorded and participants were given sufficient rest periods between trials.

An ultrasound system (a Telemed Echoblaster 128 CEXT system, UAB Telemed, Vilnius, Lithuania) with a 10 MHz linear wideband array transducer (model: HL9.0/60/128Z) was used to capture foot muscle images for muscle morphology measurements. All ultrasound measurements were taken on the right leg and foot in an unloaded position at the same reliable locations as Crofts *et al* [13] and Mickle *et al* [14]. Participants lay in a prone position for scanning FDB and QP muscles and in a supine position for the AbH and PER muscles. To capture the thickness of the muscle, the probe was placed along the direction of the muscle fiber, and for the cross-sectional area (CSA), the probe was rotated 90° at the thickest part of the muscle.

2.3. Data analysis and statistics

Ultrasound images were processed (Image J software, National Institutes of Health, Bethesda, MD, USA) by the same trained assessor to measure muscle thickness and CSA. The CSA of QP was not analyzed due to difficulty in correctly identifying the muscle border. Traditional COP parameters used in this study were the standard deviation (SD) of the COP amplitude in the anterior-posterior (AP) and medial-lateral (ML) directions and the COP ellipse area (95% confidence ellipse) [3]. In addition, SDA was used to assess the dynamic nature of the COP motion following the procedures of Collins and De Luca [23]. In line with fractional Brownian motion, short-term (Hs_{AP}, Hs_{ML}) and long-term (Hl_{AP}, Hl_{ML})

scaling exponents in the AP and ML directions determine the control system, with values greater than 0.5 indicating open-loop control, and less than 0.5 indicating closed-loop control. Additionally, short-term (Ds_{AP}, Ds_{ML}) and long-term (Dl_{AP}, Dl_{ML}) diffusion coefficients, as well as critical time (Ct_{AP}, Ct_{ML}) and critical displacement (Cd_{AP}, Cd_{ML}) were calculated from the slopes of the linear-linear mean square COP displacement versus time interval curves. These measures reflect the stochastic activity of open-loop and closed-loop postural control mechanisms in the AP and ML directions, respectively. All calculations were performed in MATLAB R2015b (Mathworks, Boston, MA, USA).

The correlation between foot muscle morphology and traditional COP parameters, as well as with SDA parameters (only where statistically significant, i.e. $p < 0.05$, associations with traditional COP parameters were observed) was examined using Pearson correlation coefficients. Differences of COP ellipse area between foot types were assessed using a one-way ANOVA. P-values less than 0.05 were considered statistically significant. All measures were normally distributed (Shapiro-Wilk test) and all statistical analyses were performed using SPSS version 22 (SPSS Science, Chicago, Illinois).

3. Results

Participants' characteristics including foot muscle morphology, COP sway parameters and SDA parameters are listed in Table 1. Mean short-term scaling exponents (Hs_{AP}, Hs_{ML}) for all participants were greater than 0.5, indicating open-loop control, and long-term scaling exponents (Hl_{AP}, Hl_{ML}) were less than 0.5 in both the AP and ML directions, indicating closed-loop control.

The COP ellipse areas were not different between foot types (depending on FPI scores) and therefore correlation analysis was performed on all participants pooled together. Pearson's correlations between relevant muscles with traditional COP variables are shown in Table 2. Larger AbH was related to smaller COP sway: with AbH-CSA negatively correlated with ML_SD and AbH thickness negatively correlated with AP_SD, ML_SD, and the COP ellipse area. On the other hand, larger PER was related to larger COP sway: with PER-CSA positively correlated with ML_SD and COP ellipse area ($p<0.01$) and PER thickness positively correlated with ML_SD. There were no associations between either FDB or QP muscle size and COP parameters.

Only AbH and PER showed significant relationships with traditional COP measures, and therefore only these muscles were subjected to post hoc Pearson's correlations with SDA measures (**Table 3).** AbH-

CSA was negatively correlated with medial-lateral critical displacement (Cd_{ML}) while AbH-T was negatively correlated with anterior-posterior short-term diffusion coefficients (Ds_{AP}) and critical displacements (Cd_{AP}), as well as with medial-lateral critical time (Ct_{ML}). Examples of two participants' COP displacements and the stabilogram diffusion plots are illustrated in **Fig 1**. PER-CSA was positively correlated with medial-lateral short-term (Ds_{ML}) and long-term (Dl_{ML}) diffusion coefficients.

4. Discussion

This study examined the relationship between foot muscle morphology and balance performance on healthy recreational runners. Our results show that the AbH morphology was associated with a better balance performance and that PER morphology was related to larger COP sway, while FDB and QP demonstrated no such correlation.

Increased COP sway amplitude and velocity decreases the ability to maintain equilibrium [3]. The negative correlation between COP sway and the AbH size in our study suggests that larger AbH contributes to better balance. This result is in line with our hypothesis and there are three possible explanations for this correlation. Firstly, AbH generates force to support the medial longitudinal arch and to control pronation [24]. Previous EMG studies show that AbH is activated during static stances and that when intrinsic foot muscle function is impaired by fatigue [24] or tibial nerve block [25], larger navicular drop is observed. Secondly, other than generating forces to control motion, AbH activation increases the longitudinal arch stiffness [26], which also contributes to stabilizing the foot. Thirdly, it is suggested that plantar foot muscles contribute to intensifying sensory information to maintain balance. Tanaka *et al* showed that older people exerted greater pressure under their toes than younger people during standing, and suggested that this might be an attempt to intensify sensory input from the great toe to maintain balance [27]. Therefore, larger AbH might help provide better sensory information, assisting the central balance control system to maintain balance.

As for FDB and QP, contrary to our hypothesis, we did not find any significant correlations with COP sway data. Kelly *et al* found that muscle activations of AbH, FDB and QP were all increased during single-leg standing compared to less challenging conditions (sitting and double-leg standing), suggesting that these muscles contribute to balance control [8]. However, our results show that the AbH morphology is the only one that was associated with better balance and that the other two muscles (FDB and QP) could not explain the variability in balance performance. From an anatomic perspective, AbH may control balance more efficiently through supporting the medial longitudinal arch compared to FDB and QP, since these latter muscles run in the middle of the plantar foot. AbH is also the largest intrinsic foot muscle. As co-activation of leg muscles might contribute to stability [17], the increased recruitment of both FDB and QP from double-leg standing to single-leg standing might be due to co-activation in response to increased loading rather than to control medial-lateral balance. Further studies are warranted to determine the role of FDB and QP in balance control.

In contrast to the AbH, larger PER were associated with worse balance control. Since PER functions to stabilize the ankle-subtalar joint complex, this seems counterintuitive [28]. However, as all participants were healthy young runners able to complete 30 seconds of single-leg standing, the observed COP sway is unlikely to be indicative of a balance problem but may instead imply the strategy they used. As suggested by the foot core theory [7], intrinsic muscles stabilize the foot rather than control the motion, while extrinsic muscles act to control the global motion. Based on the results of this study, we hypothesize that intrinsic muscles contribute to minimizing COP sway, and that if the intrinsic foot muscles are not strong enough to keep the COP sway within a threshold, then larger moments are generated by extrinsic foot muscles to maintain balance. It seems that stronger PER may compensate for a less stable foot and this balance control strategy is used in people with worse balance. Another explanation is that greater PER contractions may produce more noise-like fluctuations since they are unable to produce constant force. This would lead to larger COP sway [29]. A previous study has shown that it is possible that increased leg muscle activity contributes to greater postural instability [17]. Therefore, strengthening PER to improve balance might be an inefficient training strategy since this may lead to greater compensations in medial-lateral sway and thus hinder balance.

SDA was performed in addition to traditional COP sway parameters to better understand how foot muscles affect single-leg balance control strategy. In the current study, single-leg standing COP movements over short-term intervals were not purely random, but rather exhibited behavior characteristic of open-loop control (not using sensory feedback). In contrast, single-leg standing COP movements over long-intervals exhibited behavior characteristic of a more tightly controlled process (closed-loop control system using sensory feedback). These results are in line with those previously reported when using SDA on bipedal stance [23, 30]. We found that healthy individuals with larger AbH have better anterior-posterior short-term dynamic stability (smaller Ds_{AP}), and exhibit more efficient transfers from open-loop to closed loop control in both anterior-posterior and medial-lateral directions (smaller Cd_{AP} and Cd_{ML}). It has recently been reported that short-term parameters increase significantly after plantar flexor muscle fatigue [19]. Thus, it is plausible to suggest that fatigue and perhaps weakness of the AbH muscle may exacerbate these short-term instabilities and result in poorer open-loop control. In addition, balance corrections are said to be triggered more rapidly but after longer distances in single- compared to double-leg stance [30]. In agreement, our critical transition coordinates were overall shorter temporally (Ct_{AP} and Ct_{ML}) while larger spatially (Cd_{AP} and Cd_{ML}) along both axes compared to values previously observed during double-leg stance. Thus, it could be speculated that a more efficient use of AbH as a local stabilizer may help minimize balance corrections needed during single-leg stance.

Interestingly, PER morphology parameters did not show any significant correlations with these short-term SDA parameters, but instead showed significant positive relationships with long-term diffusion coefficients in both anterior-posterior and medial-lateral directions. This latter finding may build on our aforementioned notion that individuals with poorer balance (in this case exacerbated long-term instabilities) may rely on the PER more as a closed-loop compensation strategy as opposed to providing additional stability. Although the role of extrinsic foot muscles predominately as “global movers” remains unclear, the use of SDA proved to strengthen the hypothesis that certain intrinsic foot muscles may act primarily as “local stabilizers”.

There are several limitations to the current study. Firstly, our results are specific to this group of recreational young runners, who were able to manage 3 trials of 30 seconds of single leg standing. Therefore, the results might be difficult to extend to other populations, e.g. the elderly. Additional studies on different populations are needed to further elucidate how foot muscles contribute to balance control. Secondly, the compression applied on the skin during the ultrasound measurement might lead to underestimating the thickness of the muscles. All measurements were therefore performed by one trained assessor who applied minimal compression on the skin during all measurements. As such, we believe that the loads applied during the measurements were minimal and consistent between participants.

In conclusion, our results show that larger AbH is related to smaller COP sway, while larger PER demonstrated an opposite trend. A possible balance control mechanism might be that if the intrinsic muscles are not strong enough to stabilize the foot, larger forces are provided by the extrinsic muscles. Our SDA results indicate that AbH also has an influence on balance control mechanisms, with larger AbH contributing to better balance during open-loop control and to more efficient transition from open-loop control to closed-loop control. We suggest that strengthening the intrinsic foot muscles may be a more efficient way to improve balance.

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Figure Caption

Figr-1**Fig. 1. A)** Visual comparison of two representative participants with differing AbH muscle size (not to scale): one participant with small AbH (participant A in dark grey) and one participant with large AbH (participant B in blue). Stabilogram diffusion plots are shown for both **B**) anteroposterior and **C**) mediolateral directions for these two participants. SDA parameters derived from these plots were: short-term and long-term diffusion coefficients Ds_{AP} , Dl_{AP} , Ds_{ML} and Dl_{ML} (dashed lines; derived from the slopes of the lines fitted to the short-term and long-term regions respectively) as well as critical transition points [Ct_{AP}; Cd_{AP}] and [Ct_{ML}; Cd_{ML}] (red circles; indicating time and displacement of the approximated transition from open-loop to closed-loop control).

Table 1 Mean (SD) value for each parameter measured (n = 31)

Parameter	Mean	SD
FPI	3.1	3.2
Age	25.6	6.0
BMI	21.8	2.2
Foot muscle morphology		
AbH-CSA (mm^2)	257.8	52.2
AbH-thickness (mm)	12.1	1.1
FDB-CSA (mm^2)	230.5	48.1
FDB- thickness (mm)	9.8	1.4
QP- thickness (mm)	10.1	1.2
PER-CSA (mm^2)	403.4	70.3
PER- thickness (mm)	13.9	1.7
COP sway		
AP_SD (mm)	7.2	1.4
ML_SD (mm)	8.6	2.0
ellipse area (mm^2)	1185.4	442.3
SDA parameters		
Ds_{AP} (mm^2/s)	103.62	48.52
Dl_{AP} (mm^2/s)	1.72	2.19
Ds_{ML} (mm^2/s)	88.18	36.05
Dl_{ML} (mm^2/s)	4.71	3.60
Hs_{AP}	0.86	0.06
Hl_{AP}	0.06	0.05
Hs_{ML}	0.73	0.07
Hl_{ML}	0.14	0.07
Ct_{AP} (s)	0.88	0.15
Cd_{AP} (mm^2)	85.53	29.92
Ct_{ML} (s)	0.90	0.16
Cd_{ML} (mm^2)	96.87	46.47

AbH (abductor hallucis), FDB (flexor digitorum brevis), QP (quadratus plantae) and PER (peroneal muscles).

Table 2 Pearson correlations between foot muscle morphology and traditional COP measures (n = 31)

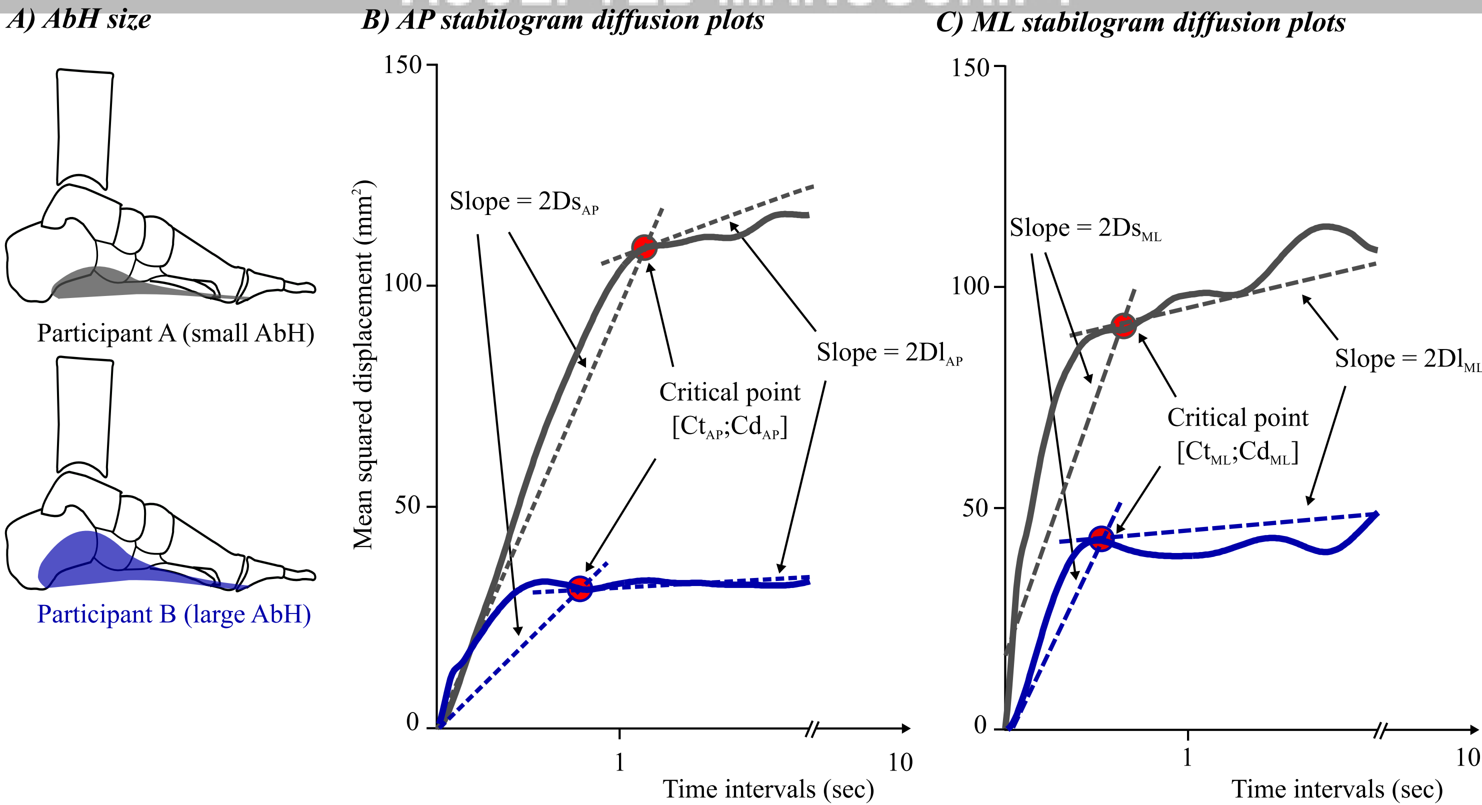
	AP_SD	ML_SD	COP ellipse area
AbH-CSA	-0.099	-0.409*	-0.269
AbH thickness	-0.477**	-0.374*	-0.435*
FDB-CSA	0.202	0.192	0.229
FDB thickness	0.249	0.196	0.228
QP thickness	0.249	0.056	0.179
PER-CSA	0.262	0.548**	0.457**
PER thickness	0.228	0.364*	0.326

AbH (abductor hallucis), FDB (flexor digitorum brevis), QP (quadratus plantae) and PER (peroneal muscles). *p<0.05, **p<0.01.

Table 3 Pearson correlations between AbH and PER foot muscle morphology with SDA (n = 31)

	Ds_{AP}	Dl_{AP}	Ds_{ML}	Dl_{ML}	Ct_{AP}	Cd_{AP}	Ct_{ML}	Cd_{ML}
AbH-CSA	-0.100	-0.033	-0.348	-0.304	-0.049	-0.104	-0.186	-0.495**
AbH thickness	-0.408*	-0.108	-0.171	-0.221	-0.164	-0.503**	-0.471**	-0.295
PER-CSA	0.085	0.097	.387*	.550**	-0.016	0.204	-0.237	0.247
PER thickness	0.021	0.099	0.324	0.304	0.013	0.151	-0.304	0.09

***p<0.05, **p<0.01.**


A) AbH size
Participant A (small AbH)
Participant B (large AbH)
B) AP stabilogram diffusion plots
Mean squared displacement (mm²)
150
100
50
0
Slope = 2Ds_AP
Critical point
[Ct_AP;Cd_AP]
Slope = 2Dl_AP
1
10
Time intervals (sec)
C) ML stabilogram diffusion plots
150
100
50
0
Slope = 2Ds_ML
Critical point
[Ct_ML;Cd_ML]
Slope = 2Dl_ML
1
10
Time intervals (sec)