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Morphology of the toe flexor muscles in older people with toe deformities

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Running head: muscle size and toe deformities

Abstract

Objective: Despite suggestions that atrophied, or weak toe flexor muscles are associated with the formation of toe deformities, there has been little evidence to support this theory. This study aimed to determine whether the size of the toe flexor muscles differed in older people with and without toe deformities.

Methods: Forty-four older adults (>60 years) were recruited for the study. Each participant had their feet assessed for the presence of hallux valgus or lesser toe deformities. Intrinsic and extrinsic toe flexor muscles were imaged with an ultrasound system using a standardised protocol. Assessor blinded muscle thickness and cross-sectional area was measured using Image J software.

Results: Participants with lesser toe deformities (n=20) were found to have significantly smaller quadratus plantae (p=0.003), flexor digitorum brevis (p=0.013), abductor hallucis (p=0.004) and flexor halluces brevis (p=0.005) muscles than the participants without any toe deformities (n=19). Female participants with hallux valgus (n=10) were found to have significantly smaller abductor hallucis (p=0.048) and flexor halluces brevis (p=0.013) muscles than the female participants without any toe deformities (n=10; p<0.05).

Conclusion: This is the first study to use ultrasound to investigate the size of the toe flexor muscles in older people with hallux valgus and lesser toe deformities compared to otherwise healthy older adults. The size of the abductor hallucis and flexor hallucis brevis muscles were decreased in participants with hallux valgus whereas the quadratus plantae, flexor digitorum brevis, abductor hallucis and flexor halluces brevis muscles were smaller in those participants with lesser toe deformities.

Keywords: hallux valgus; ultrasonography; foot muscles; muscle weakness

Significance and Innovations

- The intrinsic foot muscles of older people with hallux valgus and lesser toe deformities are significantly smaller than older people without toe deformities
- Strengthening the intrinsic toe muscles may be able to reduce the incidence and severity of toe deformities in older people

Toe deformities are highly prevalent in older people. Reports indicate 35-74% of older men and women having some degree of hallux valgus [1, 2], while approximately 60% of older people display deformities of toes 2-5 (claw, hammer or mallet toes) [1, 3]. Toe deformities (regardless of underlying disease/cause) typically lead to calluses due to friction from footwear [4, 5] and can result in difficulty with fitting footwear, physical discomfort and aesthetic concerns. The presence of hallux valgus and lesser toe deformities has also been associated with poorer performance in balance and functional tests [6] and is an independent predictor of falls, whereby those with a lesser toe deformity have been found to be twice as likely to fall than those without a deformity[7].

The pathomechanics of toe deformities is not well understood, but it is thought that an imbalance between the toe flexor and extensor muscles may be a primary cause of claw and hammer toe deformities [4, 8]. Despite suggestions that atrophied, or weak toe flexor muscles are associated with the formation of toe deformities[4], there has been little evidence to support this theory. Mickle et al found that older people with hallux valgus and lesser toe deformities had weaker flexor muscles of the hallux and lesser toes, respectively[7]. However, the contribution of the intrinsic vs extrinsic muscles to this weakness, has not been explored. The intrinsic and extrinsic toe flexors have differing roles during walking and maintaining arch support, with cadaveric data demonstrating altered forefoot contact area and loading in the presence of extrinsic toe flexor dysfunction [9]. Therefore identifying weakness in a group of muscles may inform us of the functional implications of the deficiency or help explain mechanisms for the deformities.

Muscle morphological characteristics such as cross-sectional area provide information on the functional capacity of muscles, particularly when it is difficult to obtain strength or muscle activity from isolated muscles. However, little empirical evidence is available on the morphology of the foot muscles in feet with toe deformities. Locke [10]measured muscle fibre cross-sectional area of the flexor digitorum brevis muscle in two cadavers with claw toes and found that they had a larger fibre CSA than two cadavers with rectus toes, but there were obvious limitations to this study (small sample size, alterations to tissue associated with embalming and histological processing, and lack of cadaver medical history). More recently, a sonographic study showed that the thickness and cross-sectional area of the abductor hallucis muscle was reduced in people with hallux valgus[11], however this was the only foot muscle measured.

There are currently few conservative treatment options for these toe deformities. A better understanding of the pathomechanics, in particular the muscles affected by the deformities, may help inform better treatment options. For example, exercises targeting either the intrinsic or extrinsic muscles may restore strength if it were found to be limited and could help improve toe control, which is directly linked plantar contact area and balance maintenance. Therefore the purpose of this study was to determine the difference in the size of intrinsic and extrinsic toe flexor muscles in older people with and without toe deformities.

Patients & Methods

Participants

Potential participants were recruited from the community (Manchester, United Kingdom) via advertisements. Each volunteer was required to be aged over 60 years, be independently living, be able to ambulate for at least 10 m and English speaking. Participants were excluded from the study if they had foot surgery or toe amputation or a history of neurological disorders. Written informed consent was obtained from each participant and their rights were protected throughout the study. Ethics approval was obtained from the University's Research Ethics Panel (REP10/062).

Each particiant had their feet assessed using the Foot Posture Index and the presence of any lesser toe deformities (e.g. claw/hammer toes) were recorded. The Foot Posture Index is a valid and reliable 6-item foot posture observation assessment, that classifies the foot as pronated (score >5), normal (score 0-5) or supinated (score <0)[12]. Toes were defined as having a claw or hammer toe if the metatarsophalangeal joint was in an extended position [4]. Furthermore, the degree of hallux valgus (none, mild, moderate or severe) was rated for each foot using the Manchester Scale [13]. The test foot was based on the presence of deformity. If a unilateral toe deformity was present, that was the test foot. If bilateral deformity or no deformity was present, the dominant stance limb (preferred single-leg stance leg) was assigned the test foot. If a participant had unilateral hallux valgus and a lesser toe defomity present, but on contralateral limbs, the foot with hallux valgus was the test foot, as this deformity is less prevalent. Height (m) and weight (kg) were also recorded and the body mass index (BMI, kg/m2) was calculated.

Ultrasound

The abductor hallucis, flexor hallucis brevis, flexor digitorum brevis, quadratus plantae and abductor digiti minimi muscles in the foot (see Figure 1) and the flexor digitorum longus and flexor hallucis longus muscles in the shank were the muscles of interest as they are the main contributors to toe flexion. Each muscle was imaged using a Venue 40 musculoskeletal ultrasound system (GE Healthcare, United Kingdom) fitted with either a 5-13 (maximum depth 6 cm) or 8-18 MHz (maximum depth 4 cm) linear transducer. The abductor hallucis, flexor digitorum longus and flexor hallucis longus were imaged with the participants lying supine with their hip externally rotated and knee slightly flexed. For the flexor digitorum brevis, quadratus plantae, flexor hallucis brevis and abductor digiti minimi muscles, participants lay prone on a plinth with their feet hanging freely.

Images of the muscles were obtained using a standardized procedure that has been shown to have high intra- and inter-rater reliability [14, 15]. Ultrasound coupling gel was applied over the transducer and skin at each of the measurement sites. To optimize image quality, the transducer was positioned so that the ultrasound beam was aimed perpendicular to the muscle borders. Depth and gain were adjusted to obtain a satisfactory image and then the image was captured when muscles were in a relaxed state. The tester applied minimal pressure to the ultrasound probe in order to reduce deformation of the muscle and surrounding tissues. Three images were taken at each site, removing the probe between each trial. Muscle thickness (cm) and cross-sectional area (cm^2) were measured using Image J software (National Institute for Health, Bethesda, MD, USA) and averages calculated.

Statistical analysis

Participants who had moderate-to-severe hallux valgus were assigned to the hallux valgus group (HV), and those who had lesser toe deformities present formed the lesser toe deformity group (LTD). Individuals who had no toe deformities formed the control group. For all analyses, the two toe deformity groups were only compared with the control group.

Data was checked for normality using a Kolmogorov-Smirnov test, and all variables were found to be normally distributed. Participant characteristics of the groups were compared using independent t-tests. To investigate whether any of the participant characteristics that differed between groups had a relationship with the independent variables, Pearson correlation coefficients were calculated (age, foot posture, height) or independent t-tests performed (gender).

To determine whether there were any associations between toe deformities and muscle size, the cross-sectional area and thickness of the toe flexor muscles of participants with moderate-to-severe hallux valgus or lesser toe deformities were compared to those without toe deformities using independent *t*-tests. An alpha of $P<0.05$ was established for all statistical analyses, which were conducted using SPSS software (IBM SPSS Statistics 22).

Results

Twenty-five participants (16 women, 9 men) with a mean (± SD) age of 70.6 ± 5.2 years presented with toe deformities (20 with lesser toe, 11 with hallux valgus and 5 with both).

Nineteen controls (10 women, 9 men) with a mean ± SD age of 66.7 ± 3.0 years also participated. The characteristics for each participant group are detailed in Table 1. All participants were within the age range of 60-81 years; however the control group was statistically younger (by approximately 5 years) than the toe deformity groups. The groups were evenly matched for BMI, however there was a significantly higher proportion of females in the hallux valgus group (91%), compared to the control group (53%). This gender difference resulted in the hallux valgus group being significantly shorter in height than the control group. Furthermore participants with hallux valgus had a significantly higher foot Posture Index than the control group.

Age, height and Foot Posture Index did not significantly correlate with any of the independent variables; however, the males had significantly larger AHB, QP and FDB muscles but a thinner FDL muscle than the female participants. Therefore, due to there being only 1 male in the hallux valgus group, only female participants from the hallux valgus (n=10) and control (n = 10) groups were used for the statistical comparison.

The female participants with hallux valgus had significantly reduced cross-sectional area of the abductor hallucis (-14%) and flexor hallucis brevis (-25%) muscles ($P < 0.05$), however the remaining muscles were very similar in size between the two groups (see Figure 2). All participants (males and females) with lesser toe deformities were found to have reduced cross-sectional area of the abductor hallucis (-11%), flexor hallucis brevis (-23%) and quadratus plantae (-14%) muscles compared to all the participants without toe deformities (see Figure 3). Furthermore, the thickness of the abductor hallucis (-9%), flexor hallucis brevis (-12%), quadratus plantae (-18%) and flexor digitorum brevis (-14%) muscles were all significantly reduced in the group with lesser toe deformities than the control group (see Figure 4).

Discussion

This paper aimed to determine if there were any differences in the size of the toe flexor muscles in older people with hallux valgus and lesser toe deformities compared to otherwise healthy older adults without foot deformities. We found that the female participants with moderate-to-severe hallux valgus had significantly smaller abductor hallucis and flexor hallucis brevis muscles than the female participants without any toe deformities. Similarly, participants with lesser toe deformities had significantly smaller quadratus plantae, flexor digitorum brevis, abductor hallucis and flexor hallucis brevis muscles than the participants without any toe deformities. In comparison to previous studies that have reported muscle size in people with hallux valgus, the cross-sectional area of the abductor hallucis muscle in the participants in this study (214 mm^2) was very similar to that reported by Kim et al [16] (204 mm^2), but slightly smaller than those in the study by Stewart et al [11](272 mm^2) and the 65+ year olds in with hallux valgus in the study by Aiyer et al [17] (289 mm^2). However, the thickness of the abductor hallucis muscle the participants with hallux valgus in this study, Stewart's [11] and the older adults in Aiyer's study [17] were very similar (11.5 mm vs 11.3 mm vs 11.9 mm). This study is the first to comprehensively investigate the association between muscle morphology of numerous toe flexor muscles and toe deformities and we will discuss our findings below.

The reduction in size of the abductor hallucis and flexor hallucis brevis muscles in the hallux valgus group support the findings of previous studies, whereby people with hallux valgus had significantly reduced hallux flexor strength [7, 18], hallux abduction strength [18] and a smaller cross-sectional area of the abductor hallucis muscle [11] than those without the deformity. The cross-sectional design of this study does not allow us to determine the mechanism of the associations; whether smaller/weaker muscles lead to the formation of the deformity, or whether the deformity leads to muscle atrophy. For example, in more severe degrees of hallux valgus deformity, particularly in cases where the hallux overlaps the second toe, the extensor hallicus longus tendon shifts towards the fibula [19]. This will place tension on the tendon, holding the hallux in extension. In addition to increased joint stiffness joint as the metatarsal and phalanx become misaligned and osseous changes occur, the altered joint mechanics will reduce the capacity of the flexor muscles to actively contract against the ground. Alternatively, if atrophied through disuse, the abductor hallucis muscle cannot adequately resist the pull from the adductor muscles which may lead to adduction of the phalanx (towards to midline of the foot). This is supported by the findings of a markedly decrease in the muscle activity of abductor hallucis during abduction when compared with adduction of adductor hallucis in people with hallux valgus [20].

The abductor hallucis muscle originates at the medial process of the calcaneal tuberosity and inserts into the medial aspect of the proximal phalanx and sesamoid (see Figure 1). The muscle acts to maintain normal joint alignment in the face of multiple lateral structures inserting on the phalanx, thus stabilising the first metatarsal phalangeal joint, and elevating the arch [21]. Interestingly, the higher Foot Posture Index displayed by the hallux valgus group indicates that they have a more pronated foot type, or flatter arch, than the control participants. This is in agreement with studies that suggest that a flat foot type is associated with hallux valgus deformity [5], and reduced function of the abductor hallucis muscle [21-23]. It is not known whether a longer abductor hallucis muscle occurs with the flatter foot and how this might affect muscle/tendon length and thereafter capacity for force development. Smaller abductor hallucis may also affect the external visual impression of the arch height as well as the structural alignment.

Similarly, the reduction in size of the quadratus plantae and flexor digitorum brevis muscles in the toe deformity group support the findings of previous research, whereby older people with lesser toe deformities had significantly reduced strength of the lesser toes than those without toe deformities [7]. Interestingly it was the intrinsic toe flexor muscles that were smaller in the group with lesser toe deformities, but there was no difference in the size of the extrinsic flexor digitorium longus muscle between the groups. The plantar intrinsic muscles stiffen the joints of the foot and help keep the toes flat on the ground through to the push-off phase of the gait cycle [24, 25]. Conversely, the long flexor muscles cross the ankle joint therefore play a role in plantar flexion of the ankle and power and control gait accelerations [25]. Therefore it is possible that the former foot function is most affected in people with lesser toe deformities. Again, we cannot determine whether these changes in muscle structure and function are a cause or consequence of the deformity. In a foot with a lesser toe deformity, subluxation of the proximal phalangeal joint typically occurs, and this joint malalignment will alter the axis of the intrinsic toe flexors, in turn making them less biomechanically efficient [4, 26]. Alternatively, weak toe flexor muscles may not be able to counterbalance the toe extensors, which will lead to phalangeal joints maintaining an extended resting position, creating the deformity.

Both toe deformity groups displayed a significant reduction (9-25%) in the size of the intrinsic toe flexor muscles. Although some of these changes may appear to be a minor reduction, is possible that functional deficits may still be of consequence. For example, changes in CSA of the quadriceps of as little as 5-9% were accompanied by strength gains of 34-56% in middle aged to older adults [27]. More specifically to the foot, an increase in CSA of the abductor hallucis of only 6% resulted in a 14% improvement in hallux flexor strength following a intervention program that incorporated foot strengthening exercises [28]. The functional/clinical effects of minor reductions of each of the foot muscles is unknown, however, the combined loss in numerous muscles, likely contributes to reduced toe flexion force production and affects the ability of older people to control the intrinsic foot muscle moments, centre of pressure forward progression under the foot, and potential the ability to walk safely. The toes play an important role in applying pressure to the ground to ensure we maintain balance [29] [30]. If the toes cannot effectively exert pressure to the ground their mechanical role and ability to correct for postural disturbances is diminished [30]. As such, older individuals with hallux valgus and lesser toe deformities have been found to have a greater risk of having a fall, than older people without the deformities [7]. Toes are ideally placed to help assist management of ankle balance since they are the furthest away from the ankle centre and so load under the toes has a large ankle moment arm. The findings of this research should be interpreted within the limitations of the study. We did not have enough males with hallux valgus, therefore only females were included in the analysis. While hallux valgus is more prevalent in females than males, the mechanisms for the development of the deformity may differ between the sexes, particularly if footwear is implicated as some have supposed [31, 32]. Therefore, it is unknown whether the findings related to hallux valgus from this study are also applicable to males. Other intrinsic foot characteristics such as foot length and width were not taken into consideration. It is unknown whether foot size influences muscle size, however, we found no correlation between height (therefore presumably foot size) and muscle size in this cohort, therefore the data was not normalised.

However, our results suggest that it is worthwhile investigating whether strengthening the intrinsic toe muscles could reduce the incidence and severity of toe deformities. While foot exercises generally appears to be effective in increasing toe strength and improving physical performance in older people [33], there is little evidence yet to support targeted foot strengthening programs for people with toe deformities. Exercises designed to strengthen the muscles that support the first ray may be able to prevent or delay the progression of hallux valgus. Interestingly, the short foot exercise has been shown to increase the cross-sectional area of the abductor hallucis muscle [28], however this was in a study of young adults with pes planus. Additionally, performing great toe resisted abduction exercises was found to activate the abductor hallucis muscle more than toe spread or short foot exercises [34], but these were also in healthy young adults. Given that the size of the abductor hallucis muscle was reduced in the participants in this study with toe deformities, these exercises may be an appropriate treatment option. Therefore, interventions aimed at reversing foot muscle atrophy in older people with toe deformities are warranted and require further investigation.

Conclusion

This is the first study to use ultrasound to investigate the size of the toe flexor muscles in older people with hallux valgus and lesser toe deformities compared to otherwise healthy older adults. The size of the abductor hallucis and flexor halluces brevis muscles were decreased in participants with hallux valgus whereas the quadratus plantae, flexor digitorum brevis, abductor hallucis and flexor halluces brevis muscles were smaller in those participants with lesser toe deformities. This could contribute to reduced toe flexion force production and affect the ability of older people with foot problems to walk safely. Therefore, interventions aimed at reversing foot muscle atrophy in older people with toe deformities are perhaps warranted and require further investigation.

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Figure Legends

Figure 1: Anatomical drawing of plantar foot muscles, indicating the superficial (left), mid (middle) and deep (right) layers. Adapted from OpenStax [35].

Figure 2: Muscle cross-sectional area (± SD) for the female participants with hallux valgus (n=10) and the female control-participants. * indicates a significant difference between the two participant groups.

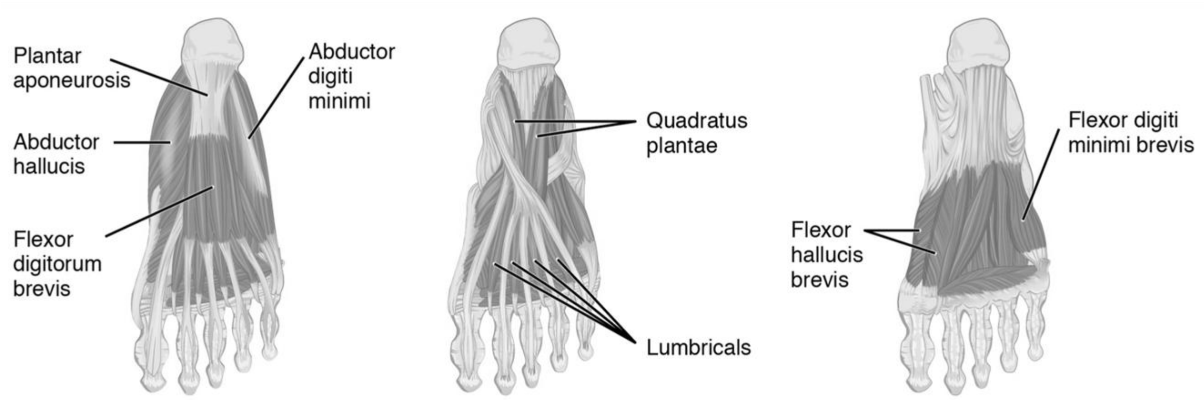
Figure 3: Muscle cross-sectional area (± SD) for the participants with lesser toe deformities and the control-participants. * indicates a significant difference between the two participant groups.

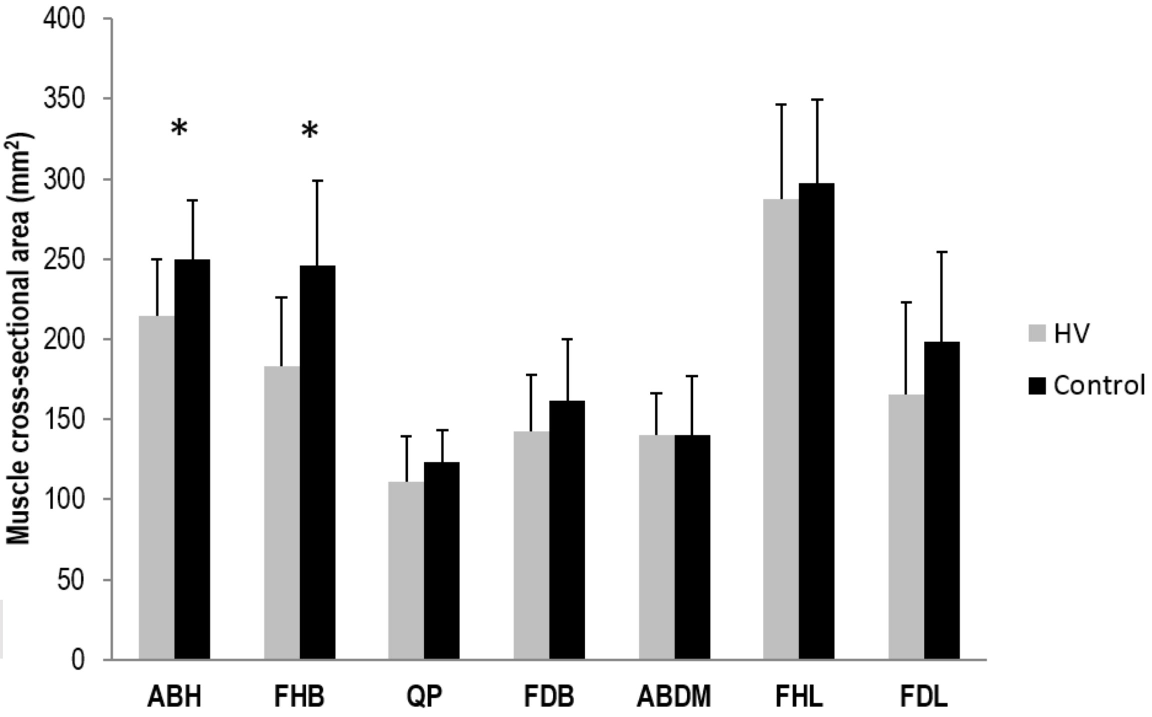
Figure 4: Muscle thickness (± SD) for the participants with lesser toe deformities and the control-participants. * indicates a significant difference between the two participant groups.

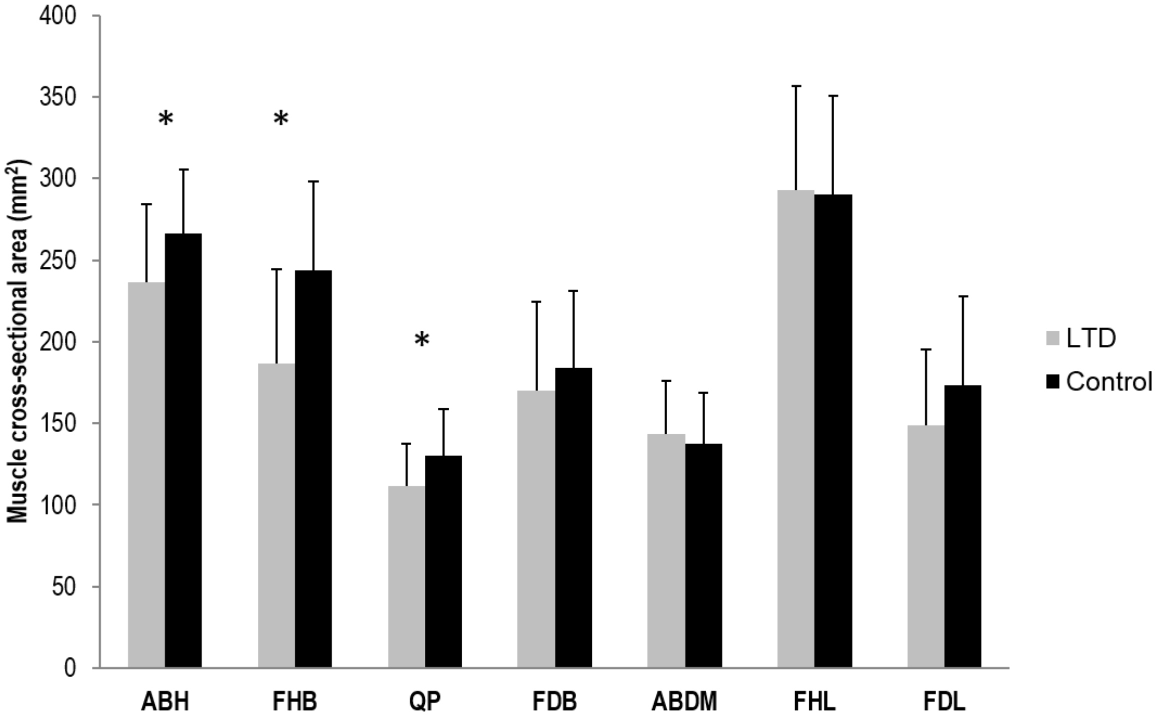
Table 1. Demographic characteristics of the hallux valgus (HV), lesser toe deformity (LTD) and control participant groups. * indicates a significant difference between the toe deformity and control groups (p<0.05).

Variable	**HV group (n = 11)**	**LTD group (n = 20)**	**Control group (n = 19)**
Age, years	70.27 (5.38)*	71.05 (5.27)*	66.74 (2.97)
Sex, M:F (% female)	1:10 (91)*	8:12 (60)	9:10 (53)
Body mass index, $kg.m^{-2}$	26.8 (6.91)	26.29 (4.12)	26.77 (4.76)
Height, m	1.58 (0.05)*	1.65 (0.1)	1.64 (0.1)
FPI, (-12 to +12)	5.0 (3.22)*	2.85 (3.47)	2.95 (1.99)

NB: 5 participants have both HV and LTD and therefore are included in both groups


Plantar aponeurosis
Abductor digiti minimi
Abductor hallucis
Flexor digitorum brevis
Quadratus plantae
Lumbricals
Flexor digiti minimi brevis
Flexor hallucis brevis


400
350
300
250
200
150
100
50
0
Muscle cross-sectional area (mm²)
*
*
ABH
FHB
QP
FDB
ABDM
FHL
FDL
HV
Control



Muscle cross-sectional area (mm²)
400
350
300
250
200
150
100
50
0
ABH
FHB
QP
FDB
ABDM
FHL
FDL
LTD
Control
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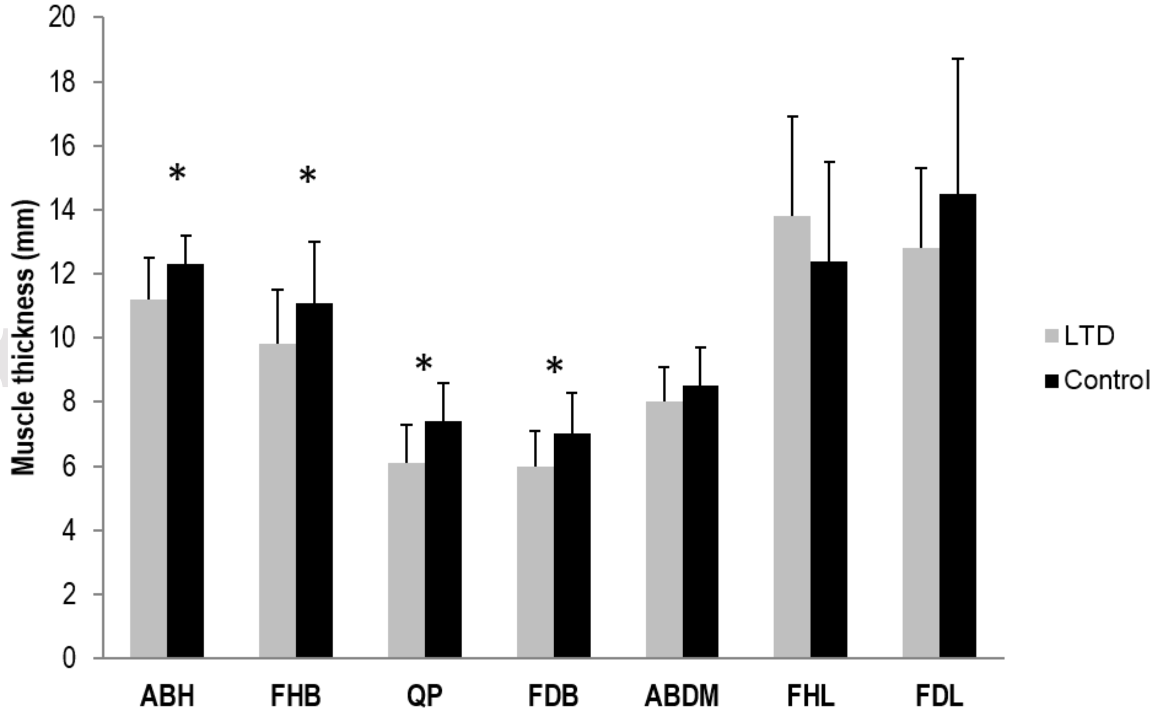

Muscle thickness (mm)
20
18
16
14
12
10
8
6
4
2
0
ABH
FHB
QP
FDB
ABDM
FHL
FDL
LTD
Control
*