Physical Therapy in Sport 42 (2020) 107–115

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original Research

Effects of a foot strengthening program on foot muscle morphology and running mechanics: A proof-of-concept, single-blind randomized controlled trial

Ulisses T. Taddei [a], Alessandra B. Matias [a], Fernanda I.A. Ribeiro [a], Sicco A. Bus [b], Isabel C.N. Sacco [a, *]

[a] Physical Therapy, Speech and Occupational Therapy Department, School of Medicine, University of São Paulo, Cidade Universitária, Rua Cipotânea 51, São Paulo, Brazil
[b] Amsterdam UMC, University of Amsterdam, Department of Rehabilitation Medicine, Amsterdam Movement Sciences, Meibergdreef 9, Amsterdam, the Netherlands

A R T I C L E I N F O

Article history:
Received 15 September 2019
Received in revised form
10 January 2020
Accepted 11 January 2020

Keywords:
Running
Sports injuries
Exercise therapy
Foot

A B S T R A C T

Objectives: To investigate the effects of a foot training program on muscle morphology and strength as well as running biomechanics in healthy recreational runners.
Design: Proof-of-concept, single-blind randomized controlled trial.
Settings: Runners were allocated to a control (CG) or an intervention (IG) group. The intervention focused on strengthening the intrinsic foot muscles and their activation during weight-bearing activities. All participants were assessed at baseline and after 8-weeks.
Participants: Twenty-eight healthy recreational long-distance runners not habituated to minimalist running shoes or barefoot running.
Main outcomes measures: Outcomes were hallux and toes strength; foot function, cross-sectional area and volume of the abductor hallucis (ABH), abductor digiti minimi (ABV), flexor digitorum brevis (FDB), and flexor hallucis brevis; medial longitudinal arch range of motion and stiffness; vertical and antero-posterior propulsive impulses during running.
Results: Compared to the CG, an increase was found in the IG for the volume of all muscles investigated and for vertical propulsive impulse during running. Correlations were found between vertical propulsive impulse and volume of ABH($r = 0.40$), ABV($r = 0.41$), and FDB($r = 0.69$).
Conclusion: The foot exercise protocol effectively increased intrinsic foot muscle volume and propulsive forces in recreational runners. This shows that intrinsic muscle strengthening affects running mechanics and suggests that it may improve running performance.

1. Introduction

The complex structure of the foot includes 26 bones, 20 intrinsic and 9 extrinsic muscles, 108 ligaments, and more than 30 joints, which all act in unison and play an important role in bipedal locomotion(Hillstrom et al., 2013; Holowka & Lieberman, 2018; Lieberman et al., 2015; Mckeon, Hertel, Bramble, & Davis, 2014). During high-intensity sports activities such as running, the foot not only needs to be compliant to assist in ground reaction force attenuation, it also be able to resist deformation and provide a stable base of support and lever arm to propel the body efficiently (Bramble & Lieberman, 2004; Luke A.; Kelly, Kuitunen, Racinais, & Cresswell, 2012; Mckeon et al., 2014). A foot that is unable to adjust to these stresses may alter resultant moments and forces acting on the more proximal joints (Buldt et al., 2015; Sawada et al., 2017, 2016), possibly leading to overuse injuries throughout the lower extremities (Mei, Gu, Xiang, Baker, & Fernandez, 2019; Son, Kim, Seeley, & Hopkins, 2019; Teng, Kong, & Leong, 2017).

In a healthy foot, the intrinsic muscles play an important role in

* Corresponding author. Department of Physical Therapy, Speech, and Occupational Therapy, School of Medicine, University of São Paulo, Rua Cipotânea, 51 - Cidade Universitária, 05360-160, São Paulo, Brazil.
E-mail addresses: ulisses.taddei@usp.br (U.T. Taddei), alessandra.matias@usp.br (A.B. Matias), fernanda.iacovanduano@gmail.com (F.I.A. Ribeiro), s.a.bus@amc.uva.nl (S.A. Bus), icnsacco@usp.br (I.C.N. Sacco).

https://doi.org/10.1016/j.ptsp.2020.01.007
1466-853X/© 2020 Elsevier Ltd. All rights reserved.

maintaining the foot arches; absorbing, dissipating, and returning kinetic energy during running; and generating power and torque (Fukano & Fukubayashi, 2009; Ker, Bennett, Bibby, Kester, & Alexander, 1987). Evidence shows that when these intrinsic foot muscles are weak or dysfunctional, these roles are compromised (Miller, Whitcome, Lieberman, Norton, & Dyer, 2014; Nigg, 2009), increasing loads on other foot passive structures, promoting excessive protonation, compromising performance, and increasing the incidence of foot deformities (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999; Mickle, Munro, Lord, Menz, & Steele, 2009; Miller et al., 2014) and injuries.

There is evidence, though, that simple foot interventions, even in healthy young subjects, are enough to change foot deformities, and improve performance. Kim et al. (Kim et al., 2015) studied the effects of different treatment approaches on individuals (19 to 29 yrs old) with hallux valgus. The participants were divided in two groups: one receiving only foot orthosis and the second, receiving additionally to the orthosis, a foot training that included a toe spreading exercise 20 min/day, 4 days/week. The study showed superiority of the training group, where individuals had increased the abductor hallucis cross-sectional area and reduced significantly the hallux valgus angle. Regarding the enhancement in sport performance, Unger and Wooden (Unger & Wooden, 2000) observed a positive effect on vertical and horizontal jumping performance after 6 weeks of a toe flexor strengthening in healthy physically active subjects. Similarly, Goldmann et al. (Goldmann, Sanno, Willwacher, Heinrich, & Brüggemann, 2012) also observed an increased performance in the jump performance after 7 weeks of toe flexor muscle training in healthy males.

The seminal paper by Robbins and Hanna (Robbins & Hanna, 1987) showed that merely encouraging healthy subjects to perform weight bearing activities at home and outdoors as much as possible without wearing any footwear resulted in an increased arch height.

Although few physical therapy programs for muscle strengthening include foot-specific strengthening strategies, studies on training the intrinsic and extrinsic foot muscles have shown promising results. Mulligan and Cook (Mulligan & Cook, 2013) found that strengthening the foot muscles using a single at-home foot exercise daily for 4 weeks lowered the navicular drop by an average 14%. Lynn, Padilla, and Tsang (Lynn, Padilla, & Tsang, 2012) compared two different exercises (towel curl and short foot) in two groups of healthy subjects and showed that after a 4-week period, the center of pressure displacement during the star excursion test decreased in both groups, indicating the positive effect of foot muscle strength on functional balance tasks. Mickle et al. (Mickle, Caputi, Potter, & Steele, 2016) were able to improve hallux and lesser toe strength, single leg balance, and general foot health of subjects aged between 60 and 90 years using a customized progressive Toe Training exercise program, showing that even elderly people benefit from foot training. The program developed was taught in 45-min weekly sessions over 12 weeks.

These findings led to the question of how changes in muscle strength affect running. Knowing the role of the intrinsic foot muscles in storing and returning energy (Luke A Kelly, Cresswell, & Farris, 2018; Ker et al., 1987), stiffening the foot arches during running (L A Kelly, Lichtwark, & Cresswell, 2015), and being a sensorial organ (Mckeon et al., 2014), it is expected that strengthening the intrinsic muscles will improve running mechanics and performance as well as prevent injury due to impact overload, accumulated load, or fatigue. Thus, this study seeks to verify if these changes to the foot's arch, structure, and functional balance are linked to the strength gain from intervention protocols.

It is expected that improvement in foot muscle morphology and strength would lead to increased foot stiffness (Holowka & Lieberman, 2018), and that the effects of a stronger foot can be measured by improved force transmission through the foot to the ground during running. Kelly et al.(L A Kelly et al., 2015) showed that the abductor hallucis (ABH), flexor digitorum brevis (FDB), and quadratus plantae muscles had higher activation during late stance in walking and running on an instrumented treadmill. This higher activation facilitates effective foot ground force transmission, enabling higher ground reaction forces to be transmitted over a shorter period of time. Thus, the aim of this proof-of-concept, single-blind randomized controlled trial was to investigate the effects of a foot muscle strengthening and training program on foot function, intrinsic foot muscles morphology and strength, as well as running biomechanics in healthy recreational runners. We hypothesized that the training program would improve intrinsic foot muscle volume, isometric strength of the toes and hallux, propulsive forces while running, and medial longitudinal arch (MLA) mechanics.

2. Methods

2.1. Design

The study was a single-blind, proof-of-concept randomized controlled trial with two study arms.

2.2. Subjects

Twenty-eight recreational long-distance runners (Table 1) were recruited through online advertisements (Laboratory of Biomechanics website, www.usp.br/labimph) and by directly approaching running clubs located around the university campus. Participants were eligible if they ran at least 20 km but no more than 100 km per week, were between 18 and 55 years of age, and had no lower limb injury or pain in the 3 months prior to baseline assessment. Participants were excluded if they were under any physical therapy treatment at baseline, had a history of using minimalist shoes or barefoot running, presented with any orthopedic or neurologic impairment or major vascular complication, had previous lower-limb surgery, or had diabetes mellitus. All participants were assessed at baseline (T0) and after 8 weeks (T8) of the foot exercises program. After T0, participants were randomly allocated in blocks based on numbers generated by the random allocation program ClinStat (University of York, Heslington, UK) (Bland, 2015). The code for each group was kept in opaque and sealed envelopes, and an independent researcher assigned the participants to either the control group (CG) or intervention group (IG). Only the physiotherapist responsible for the intervention knew who was receiving it. Blinded examiners performed all the assessments. The trial statistician was blind to treatment allocation until the main analysis has been completed. All participants' data was kept confidential before, during, and after the study by encoding their names.

This study was part of a larger trial approved by the Research and Ethics Committee of the School of Medicine of the University of São Paulo (March 18, 2015, Protocol no. 031/15) and registered with ClinicalTrials.gov (Identifier NCT02306148 November 28, 2014). All runners consented to participation after receiving information on all details of the study.

2.3. Intervention protocol

Participants in the IG performed an 8-week foot strengthening training with a physiotherapist once a week and at least three times at home over the entire course of the study. Participants reported their completed sessions and progress in an online software tool.

Table 1
Mean and standard deviation of participants' characteristics from the Control Group (CG) and Intervention Group (IG) at baseline.

	CG (n = 14)	IG (n = 14)	p-value
Age (years)	41.6 ± 6.0	41.9 ± 7.4	0.890[a]
Height (cm)	169.40 ± 9.18	166.40 ± 7.80	0.113[a]
Sex	Male: 9; Female: 5	Male: 5, Female: 9	0.131[b]
Body mass (kg)	75.1 ± 13.9	68.3 ± 12.7	0.110[a]
Running experience (years)	10.9 ± 7.9	6.2 ± 6.3	0.095[a]
Running volume (km)	30.8 ± 13.4	28.5 ± 9.5	0.639[a]
Average pace (min/km)	6.4 ± 1.3	6.4 ± 0.9	0.843[a]
Foot posture index (median, min:max) (Redmond, Crane, & Menz, 2008)	Right: 2, −4:9 Left: 2.5, −3:8	Right: 1.5, −6:10 Left: 2.5, −6:10	0.369[a]
Arch index (Cavanagh & Rodgers, 1987)	Right: 0.23 ± 0.16 Left: 0.16 ± 0.03	Right: 0.22 ± 0.10 Left: 0.16 ± 0.04	0.277[a]
Previous running-related injury more than 3 months before the beginning of the study (%)	21.4%	28.6%	0.225[b]

[a] p-values of t-tests.
[b] p-values of chi-square tests.

Participants in the CG were instructed to perform an 8-week 5-min warm-up and full body muscle stretching protocol before or after each running session. More details on the strengthening and stretching protocol are available in the published protocols for the trial (Matias, Taddei, Duarte, & Sacco, 2016). Adherence was monitored every locally supervised session and accounted as the number of sessions attended by the participants in the IG, where 100% of adherence would be a total of 112 completed sessions (14 subjects attending all 8 sessions).

2.4. Outcome measurements

For this proof-of-concept study, the main theoretical outcomes were related to the effectiveness of the intervention in improving foot function, foot muscle strength and foot biomechanics during running. These include hallux and toe isometric strength, intrinsic foot muscle anatomical cross-sectional area (ACSA) and volume, MLA range of motion (ROM) and stiffness, foot function scores, and propulsive impulses during running (vertical and antero-posterior).

Foot muscle isometric strength was measured using a pressure platform (EMED, Novel, Munich, Germany), which is a reliable way to measure foot muscle strength (Mickle, Chambers, Steele, & Munro, 2008). While standing with knees extended, participants pushed down as hard as possible using only their hallux and toes. During the assessment, the researcher checked whether the subject lifted the heel and inspected for fluctuations in the line of gravity and trunk posture during each trial. The runners were instructed to not curl their toes or grip the platform during the trial. Prior to the test, the runners were allowed to practice the movement to ensure comprehension of the task. If any changes were observed in the line of gravity or positioning of the heel or trunk, the trial was excluded. The outcome of the measurement was the peak force under the area of a mask, including the hallux and toes, normalized by bodyweight (BW) and reported as % BW.

The ASCA of the of the ABH, abductor digiti minimi (ADV), flexor hallucis brevis (FHB), and FDB were measured using magnetic resonance imaging of the right foot of each subject at T0 and T8 by the same technician following the protocol described by Matias et al. (Matias et al., 2016). ASCA was measured by a blinded researcher using ImageJ planimeter software (company, city, country) following the protocol by Miller et al.(Miller et al., 2014). Muscle volume was calculated by multiplying the sum of each ACSA measured for a specific muscle from each individual slice by the linear distance between slices (5 mm) (Miller et al., 2014).

Participants answered to the Foot Health Status Questionnaire (FHSQ) (Ferreira et al., 2008) at baseline and after 8-weeks and all eight domains were assessed: foot pain, function, shoe, general foot health, general health, physical activity, social capacity and vigor.

Foot biomechanics were assessed by having participants run barefoot on an instrumented treadmill (force plates at 1000 Hz) surrounded by eight infrared cameras (Vicon® VERO, Vicon Motion System Ltd., Oxford Metrics, UK; at 200 Hz) at a self-selected speed. The self-selected speed chosen at baseline was also used for assessment at T8. Foot kinematics were acquired based on 16 reflexive-passive markers (10 mm in diameter) placed on each subject's foot according to the Rizzoli Orthopedics Institute Foot Model (Leardini et al., 2007; Portinaro, Leardini, Panou, Monzani, & Caravaggi, 2014). Based on residual analysis (Winter & Patla, 1997), kinematic and ground reaction force data were analyzed and processed using a zero-lag, fourth-order Butterworth filter and a low-pass filter with cutoff frequencies of 15 Hz and 100 Hz, respectively.

The outcomes chosen to represent the foot biomechanical responses to the exercise protocol were the ROM of the MLA during the stance phase of running and MLA stiffness during running. The MLA angle (Fig. 1) was calculated as the angle formed by three reflective markers: at the upper central ridge of the calcaneus posterior surface, at the medial apex of the tuberosity of the navicular, and at the dorsomedial aspect of the first metatarsal-phalangeal joint, with the navicular tubercle as the MLA vertex.

MLA stiffness (k_{mid}) was calculated according to Holowka, Wallace, and Lieberman (Holowka, Wallace, & Lieberman, 2018):

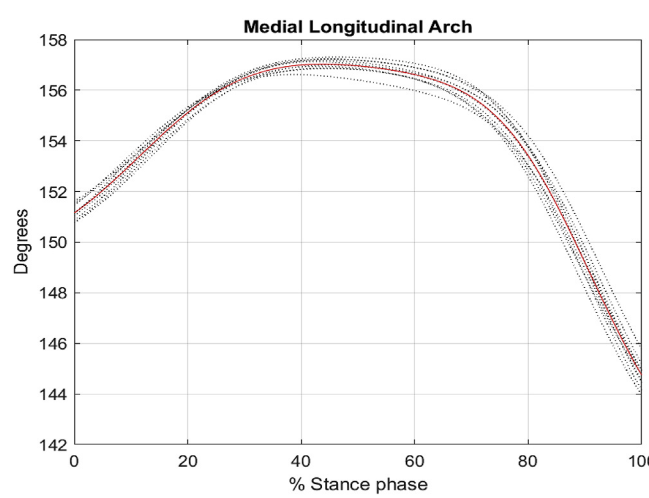

Fig. 1. Temporal series of the MLA angle of 10 trials of a random participant (average in red) during running, normalized in time by the stance phase. The curve shows more obtuse angles of the arch during mid-stance. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$k_{mid} = F_{mid}/\Delta LA_{height} \quad (1)$$

where K_{mid} is equal the vertical ground reaction force (VGRF) on the platform at 50% stance phase (F_{mid}) divided by the perpendicular distance between the navicular tuberosity marker to the line connecting the calcaneus marker to the first metatarsal head marker. Vertical impulse was calculated by integrating the VGRF curve over time from the propulsive peak to the end of stance phase (Running Impulse 1), corresponding to the push-off phase of running (Fig. 2). The horizontal impulse of the accelerating phase was also calculated from the horizontal antero-posterior GRF (AP-GRF) (Fig. 2), corresponding to the propulsive horizontal impulse (Running Impulse 2). The values in Newtons were then normalized for each participant's BW.

2.5. Statistical analyses

Baseline characteristics of participants in the IG and CG were compared using two-tailed t-tests and chi-square statistics for continuous and discrete variables, respectively. A 2 × 2 repeated measures analysis of variance (ANOVA) was used to compare the interaction effect of training (foot strengthening vs. control) and time (T0 and T8) for the variables of each domain of the FHSQ, foot strength, muscle volume, muscle ACSA, MLA ROM, MLA stiffness, and impulses. In case of significant interaction effects, Tukey's HSD test was used to conduct pairwise comparisons to identify differences in time, group, or both. The minimal detectable change (MDC) for each variable was calculated according to Haley and Fragala-Pinkham (2006) as MDC = z-score (95% CI) × SEM × $\sqrt{2}$, in which the standard error of the mean (SEM) was obtained as follows SEM = SD × $\sqrt{(1 - ICC)}$, where SD is the standard deviation and ICC is the intraclass correlation coefficient. Two-way mixed effects model ICC's were calculated using only the CG variables between T0 and T8. After that, each difference between T8 and T0 for the IG larger than the calculated MDC for the CG was accounted as an event and the event rates were compared between the two groups as relative risks (RR = absolute risk of event in the CG/absolute risk of event in the IG). The absolute risk (AR) was calculated as the number of events in the IG or CG, divided by the number of people in that group. In the case of no events of change in a variable greater than the MDC in one of the groups, only the AR was reported.

Pearson's product-moment correlations were performed to verify correlations between the studied variables at baseline (T0) for both groups together, as they started from similar baseline conditions, a joint analysis could bring results that are more robust with the larger, and no intervention was performed yet. Pearson's correlations were also performed for the IG using the differences (delta) between T8 and T0 for each dependent variable. This analysis allows verifying possible relations between changes after 8 weeks (positive or negative) with muscle morphology changes. Pearson's correlation coefficients were considered fair if between 0.3 and 0.5, moderate between 0.6 and 0.7, and strong between 0.8 and 0.9 (Akoglu, 2018). Cohen's d effect size was calculated for variables with significant differences between groups, and effects between 0.2 and 0.5 were considered small, between 0.5 and 0.8 were medium, and above 0.8 were large (Lakens, 2013).

3. Results

3.1. Foot strength measurements

There was no significant interaction effect between time (T0 and T8) and group (IG and CG) for Hallux and toe flexor isometric strength (CG: T0 = 23.46 ± 4.86 %BW; T8 = 25.61 ± 7.40 %BW; IG: T0 = 19.95 ± 6.24 %BW; T8 = 27.31 ± 9.33 %BW; $p = 0.707$). At baseline, the groups were not different ($p = 0.9362$). Calculated MDC of 11.86 %BW resulted in a RR = 0.31, meaning 69% reduction in relative risk for events in the CG with a non-significant confidence interval CI = [0.04–2.61].

3.2. Foot function (FHSQ)

There were no differences at baseline between groups for any of the eight domains ($p > 0.05$). There were also no significant effects of the intervention on the FHSQ score of any domain after eight weeks ($p > 0.05$) (Table 2).

Table 2
Mean and standard deviation of the FHSQ domains scores. P-values of the interaction Group*Time for the Repeated measures ANOVAs considering significant $p < 0.05$.

	CG (T0)	IG (T0)	CG (T8)	IG (T8)	p-value
Foot Pain	89 ± 16.1	92 ± 10.9	92 ± 12.6	93 ± 11.6	0.729
Foot Function	99 ± 2.3	100 ± 1.7	100 ± 0.0	100 ± 1.7	0.327
Shoe	82 ± 13.8	81 ± 27.5	78 ± 26.5	72 ± 35.6	0.683
General Foot Health	79 ± 22.1	83 ± 26.8	83 ± 27.6	92 ± 11.6	0.548
General Health	81 ± 20.2	86 ± 10.4	90 ± 9.13	87 ± 13.8	0.184
Physical Activity	92 ± 26.6	99 ± 2.1	99 ± 2.1	100 ± 1.5	0.327
Social Capacity	91 ± 13.4	91 ± 12.9	94 ± 9.7	93 ± 10.9	0.753
Vigor	83 ± 11.1	80 ± 9.8	76 ± 10.8	78 ± 7.9	0.366

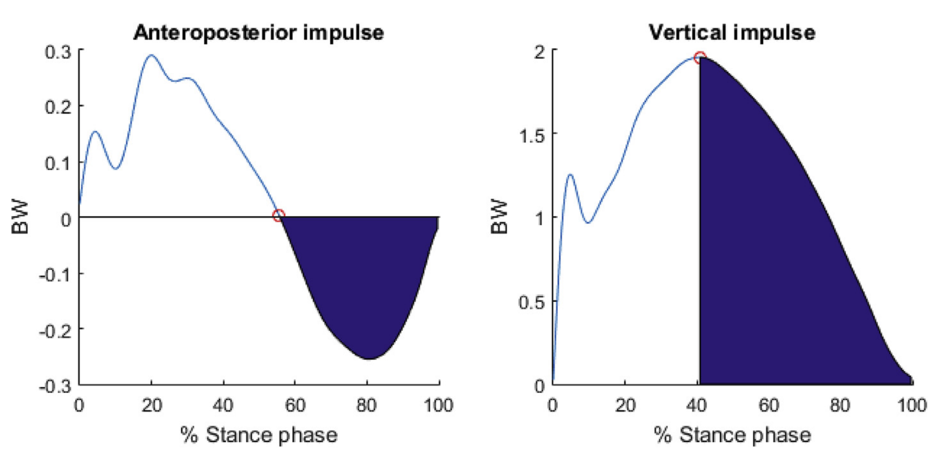

Fig. 2. Anteroposterior and vertical impulses (normalized by BW) calculated from the ground reaction force time curve during stance phase while running on a treadmill.

3.3. Intrinsic foot muscle size

There was a significant increase in the volume of all measured muscles after 8 weeks of training for the IG compared to the CG (interaction effects Time x Group for ABH: $p = 0.019$; ABV $p = 0.013$; FDB $p = 0.039$; FHB $p = 0.009$). In the IG, there was a 22.3% increase after the intervention compared to baseline for ABH, 12.1% for ABV, 8.8% for FDB, and 17.7% for FHB. At baseline, there were no differences between the groups regarding muscle size ($p > 0.05$), with the exception of the FDB muscle volume ($p = 0.028$). Values in cm^3 and Cohen's d effect sizes are reported in Table 3. The MDCs obtained were 2.8 cm^3 for ABH, 2.1 cm^3 for ABV, 1.8 cm^3 for FHB, and 3.1 cm^3 for FDB. Relative ratios could not be calculated as there were no events of increased muscle size greater than the calculated MDC in the CG, while the IG had an absolute risk of AR = 0.39 for ABH, AR = 0.31 for ABV, AR = 0.15 for FHB, and AR = 0.08 for FDB.

There were no significant differences in ACSA between the study groups after 8 weeks of intervention (ABH $p = 0.100$; ABV $p = 0.256$; FDB $p = 0.169$; FHB $p = 0.053$). At baseline, there were no differences between the groups for ACSA of any muscle studied (ABH $p = 0.104$; ABV $p = 0.142$; FDB $p = 0.267$; FHB $p = 0.066$). Calculated MDCs of 46.1 mm^2 for ABH, 31.9 mm^2 for ABV, 38.6 mm^2 for FHB, and 36.4 mm^2 for FDB showed no differences higher than the MDC between T8 and T0 in the CG, then the relative ratios could not be calculated. In the IG, no differences greater than the MDC was found for ABH, while absolute risk of the ABH was AR = 0.08, for FDB AR = 0.08, and for FHB AR = 0.23.

3.4. Propulsive impulses

There was a significant group-time interaction effect for vertical impulse in favor of the IG ($p = 0.021$). The post-hoc test revealed a significant difference ($p = 0.007$) between groups at baseline (Table 4). The MDC calculated for vertical impulse was 2.02 BWxs, without any participant showing differences higher than the MDC in the CG and an absolute risk of AR = 0.08 for the IG. There was no significant difference between groups for antero-posterior impulse over time ($p = 0.315$). MDC resulted in 2.05 BW.s with relative risk ratio of RR = 0.93, and a non-significant confidence interval CI = [0.15-5.63].

3.5. MLA range of motion

There were no significant differences between groups for MLA range of motion after 8 weeks of intervention (CG T0 = $4.6°\pm2.2°$; T8 = $4.6°\pm1.8°$; IG T0 = $4.2°\pm2.4°$, T8 = $3.6°\pm2.3°$; $p = 0.338$). There was no significant difference between the groups at baseline ($p = 0.459$). Calculated MDC of 3.43° resulted in a relative ratio RR = 0.46, meaning 54% reduction in relative risk for events in the CG with a non-significant confidence interval CI = [0.12-11.35].

3.6. MLA stiffness

No significant differences were found between groups for MLA stiffness (k_{mid}) after 8 weeks of intervention ($p = 0.781$) (Fig. 3). Calculated MDC of 57.8 $N/cm.kg^{2/3}$ revealed absolute risk of AR = 0.23 for the IG and relative ratios could not be calculated as there were no events of increased stiffness higher than the MDC in the CG.

3.7. Correlations

Pearson's correlation analysis was used to assess the relationships between variables of foot strength, muscle volume, k_{mid}, MLA range of motion, and vertical and antero-posterior impulses at baseline (T0) for all groups together (Fig. 4). Significant correlations were found for vertical impulse and muscle volume of the ABH ($r^2 = 0.160$; $p = 0.038$), ABV ($r^2 = 0.170$; $p = 0.033$), and FDB ($r^2 = 0.480$; $p < 0.001$), indicating that the stronger the intrinsic foot muscles, the more vertical impulse a participant can produce during running. There was also a significant correlation between vertical and antero-posterior impulses ($r^2 = 0.183$; $p = 0.026$). Each intrinsic foot muscle volume studied showed a significant direct correlation with the others, as shown in Fig. 4.

Pearson's correlation tests were performed for the IG using the differences (delta) between T8 and T0 to verify relationships with muscle morphology changes (Fig. 5). Significant positive correlations between ABV muscle volume and antero-posterior impulse ($r^2 = 0.370$, $p = 0.031$) was observed and an inverse relation between arch stiffness and arch range of motion ($r^2 = 0.452$, $p = 0.020$) was observed.

Regarding the adherence to the intervention, from a potential complete adherence (100%, i.e., 112 sessions), we accounted for 90 completed sessions corresponding to 80.4% adherence to the intervention. The average number of sessions attended in 8 weeks was 6.9 ± 1.6.

4. Discussion

In this proof-of-concept randomized controlled trial, we investigated the effects of a foot strength training program on muscle morphology and strength as well as foot biomechanics in recreational long-distance runners. Our hypothesis that 8 weeks of training would increase intrinsic foot muscle volume and ASCA was confirmed for the volume of all studied muscles but not for ACSA.

Regarding the role of the intrinsic foot muscles during running, it was shown that if the plantar muscles are not properly activated during walking and running, the distal foot joints will not be stiff enough to transmit propulsion forces for push-off during late stance (Farris, Kelly, Cresswell, & Lichtwark, 2019). This led us to hypothesize that any noticeable changes in running mechanics after intrinsic foot muscle training would appear during late stance.

Table 3
Mean, standard deviation, Cohen d effect sizes, p-values for repeated measure ANOVAs of ACSAs, and muscle volume.

	Group	Muscle Volume (cm^3)				Muscle ACSA (mm^2)		
		T0	T8	p-value	Cohen's d	T0	T8	p-value
ABH	CG	15.4 ± 8.1	13.3 ± 6.3	0.019	0.655	157.7 ± 79.8	145.2 ± 64.6	0.100
	IG	11.0 ± 6.1	13.7 ± 6.3			135.8 ± 64.4	141.2 ± 58.5	
ABV	CG	12.5 ± 4.6	12.0 ± 4.6	0.013	0.512	119.3 ± 33.7	113.9 ± 31.7	0.256
	IG	9.2 ± 5.0	11.2 ± 4.8			105.4 ± 36.1	112.8 ± 31.4	
FDB	CG	14.0 ± 4.6	13.3 ± 4.3	0.039	0.638	128.3 ± 44.4	122.0 ± 44.1	0.169
	IG	10.4 ± 4.6	12.5 ± 4.7			116.9 ± 45.5	116.7 ± 30.8	
FHB	CG	12.6 ± 3.6	12.0 ± 4.1	0.009	0.387	174.9 ± 37.6	166.2 ± 52.2	0.053
	IG	9.1 ± 4.8	10.2 ± 4.4			143.3 ± 38.9	147.2 ± 42.3	

Table 4
Mean, standard deviation, Cohen d effect sizes, and p-value for propulsive vertical and antero-posterior impulses in BW multiplied by seconds.

Impulse	Group	T0	T8	p-value	Cohen's d
Vertical Impulse (BW × s)	CG	74.27 ± 6.99	73.49 ± 6.47	0.021	0.367
	IG	65.86 ± 7.91	67.85 ± 9.89		
Anteroposterior Impulse (BW × s)	CG	6.17 ± 1.26	6.14 ± 1.73	0.315	0.365
	IG	5.89 ± 1.29	6.33 ± 1.75		

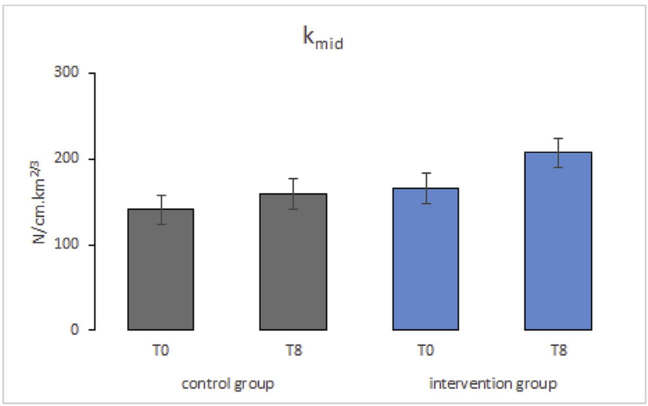

Fig. 3. Arch stiffness (k_{mid}) scaled by body mass (N/cm.kg$^{2/3}$ according to Miller et al.(Miller et al., 2014)).

The significant increase in the propulsive VGRF impulse while running confirmed this hypothesis, but not the AP-GRF impulse for the IG after 8 weeks. These main results show that 8 weeks of specific foot strength training targeting the intrinsic foot muscles can improve intrinsic muscle volume and running mechanics in recreational runners.

We found no significant effect of the training program on hallux and toe muscle strength using the pressure platform measurement, despite a significant increase in the volume of all intrinsic foot muscles. This finding might be due to the nature of the strength test, which demands specific motor control and activity of the extrinsic muscles, neither of which were included in the foot exercise protocol.

While ACSA increased in the IG group over 8 weeks, this change was not significantly different compared to the CG. This result is possibly explained by the irregular shape of the intrinsic foot muscles interfering with the way ACSA is calculated. Being the average of all slices containing the intrinsic foot muscles of interest throughout the foot scan, an increase in just one section of the muscle is attenuated by the other sections, which could make the gains statistically non-significant. Indeed, MDCs for the muscles' ACSA were higher than MDCs found for muscles' volumes. In a study by Chang et al.(Chang, Kent-Braun, & Hamill, 2012), atrophy of the intrinsic foot muscles attributed to the presence of chronic plantar fasciitis affected only the forefoot muscles with a 5.2% decrease in volume and an effect size of 0.26, while no differences were observed in rearfoot and total foot ACSA. Another explanation could be that with hypertrophy, muscle tissue can be measured in slices where previously they could not be. This also increases the number of slices containing the muscles measured, mitigating the results when calculating the average, even though a noticeable increase has occurred.

Increases in muscle volume and vertical impulse in the IG indicated that training the foot muscles can indeed alter running performance. Pearson's correlations using the difference between T8 and T0 for the IG revealed a correlation between ABV volume increase and antero-posterior impulse, although there was no significant interaction in the repeated measures ANOVA. Increased impulse could be beneficial for running performance, as found by Hunte, Marchall, and McNair (Hunter, Marshall, & McNair, 2005), who assessed 36 athletes performing maximum-effort sprints and concluded that increased vertical impulse resulted in increased sprint velocity. Similarly, Munro, Miller, and Fuglevand (Munro, Miller, & Fuglevand, 1987) found that all VGRF descriptor

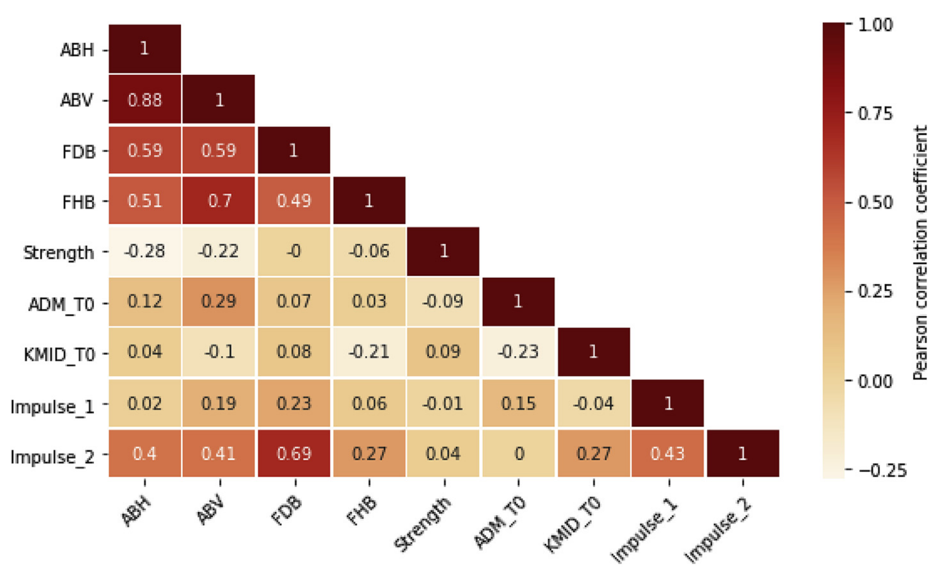

Fig. 4. Heatmap of the Pearson's product moment at T0 for all groups together between MLA stiffness (KMID), vertical (IMPULSE1) and horizontal (IMPULSE2) impulses during stance phase, MLA range of motion (MLA_ROM), flexion strength of the hallux and toes (Strength), and muscle volume of the intrinsic foot muscles (ABH, ABV, FDB, and FHB).

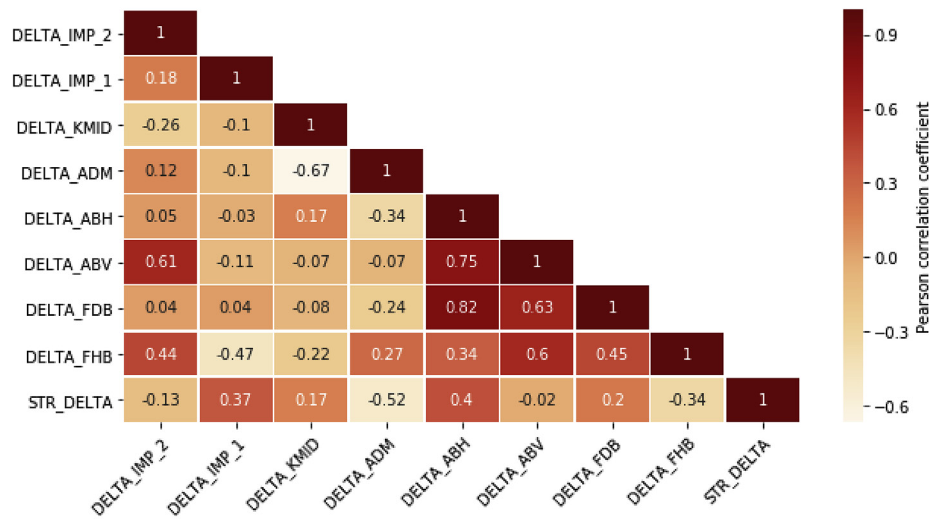

Fig. 5. Heatmap of Pearson's product moment using the differences between T8 and T0 only for the IG between the variables of MLA stiffness (DELTA_KMID), MLA range of motion (DELTA_ADM), vertical (DELTA_IMP_1) and horizontal (DELTA_IMP_2) impulses during stance phase, flexion strength of the hallux and toes (STR_DELTA), and muscle volume of the intrinsic foot muscles (ABH, ABV, FDB, and FHB).

variables increased significantly with running speed.

Similar results were found by Unger and Wooden (Unger & Wooden, 2000) after training the foot and investigating the effects on vertical and horizontal jumping performance. The authors found a significant increase in jump performance after 6 weeks of a toe flexor strengthening program in healthy physically active subjects, who also trained using similar exercises to those included in our protocol. Goldmann et al. (Goldmann et al., 2012) also found an enhancement in jump performance after 7 weeks of toe flexor muscle training in healthy males.

We did not observe changes in MLA stiffness or mechanics after the intervention nor any significant correlation between MLA stiffness and the studied variables, even though increased values for stiffness greater than the MDC were seen in the IG only. Combining kinematic and kinetic measurements during gait in the MLA stiffness calculation, Holowka, Wallace, and Lieberman (Holowka et al., 2018) showed that different populations (minimally-shod men from northwestern Mexico and conventionally-shod urban American men) had different MLA stiffnesses. Although they were able to see differences in stiffness between samples, the MLA stiffness measured was probably the effect of different lifelong habits and factors of the two very different populations. It is not certain that the same variable will be sensitive to short-period interventions such as the one in our study, which led to changes in morphology of the foot muscles but did not have the same effect size as years of barefoot activities in rough terrain, as found by Holowka et al. (Holowka et al., 2018). Therefore, further studies could focus on other variables that are possibly more responsive to foot training and intrinsic foot muscle activation during running.

Regarding the FHSQ, the lack of significant differences between groups throughout time might have also another meaning that is the inaccuracy of the chosen instrument for the studied population. As an example, for almost all the subjects assessed the Foot Function domain showed the top score at T0 and T8. If the studied population had been different regarding foot function/dysfunction or even less physically active, perhaps these results would differ, as instead of increasing performance, they would restore their foot functionality.

The attendance to the locally supervised training in the IG was considered high and satisfactory, as the runners in the IG presented 80.4% as adherence. This rate was almost above 80%, which is a threshold to consider a successful adherence ("Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009) - CEBM," n.d.).

Certain limitations exist for this study. Subjects had not previously tested for hallux and toe flexion strength using the method employed, and thus they had to learn how to avoid leaning their trunk forward or sideways or clawing their toes. After having their stance corrected by the assessor, they were successfully able to avoid these two mistakes. However, when participants pressed their toes and hallux against the pressure platform as hard as they could, they tended to also raise their foot arches and naturally shift their BW towards the calcaneus. Without leaning the trunk, a stronger participant could reach a maximum force value without losing their balance, although they had the capacity to press harder. To prevent this sort of bias, it would be wise to use a method closer to the one described by Ridge et al. (Ridge, Myrer, Olsen, Jurgensmeier, & Johnson, 2017), which used a dynamometer to assess arch doming and hallux and toe pulling strength with an apparatus that constrains the foot.

Another limitation arose from the differences in FDB muscle volume at baseline between the two groups ($p = 0.028$). This measurement was significantly smaller for the IG, which might have affected the foot strengthening results, as weaker muscles may be more responsive to training than stronger muscles. None of the other muscles showed significant group differences at baseline.

Despite these limitations, this proof-of-concept study clearly showed that the foot training protocol effectively increased intrinsic foot muscle morphology, which may have led to the changes in propulsive impulses found in the IG, since these act as a stiffer spring during late stance (Luke A Kelly et al., 2018; Riddick, Farris, & Kelly, 2019). This mechanism is reinforced by the significant correlations found between muscle volume and vertical impulse, which may result in better performance and less energy expense during running.

5. Conclusion

The 8-week foot exercise protocol effectively increased intrinsic foot muscle volume and improved vertical running propulsive forces in recreational long-distance runners. This shows that intrinsic muscle strengthening affects running mechanics and suggests that it may improve running performance.

Ethical statement

This study was part of a larger trial approved by the Research and Ethics Committee of the School of Medicine, University of Sao Paulo (Protocol no. 031/15) and registered with ClinicalTrials.gov (Identifier NCT02306148) (November 28, 2014) under the name "Effects of Foot Strengthening on the Prevalence of Injuries in Long Distance Runners.". All runners consented to participation signing a consent form after receiving information on all details of the study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the São Paulo Research Foundation [FAPESP 2015/14810-0]; Matias was awarded by the FAPESP [2014/27311-9], and Taddei was awarded by the Agency Coordination of Improvement of Higher Education Personnel (CAPES, financial code 001). Sacco is a fellow of the National Council for Scientific and Technological Development, Brazil (CNPQ Process: 304124/2018-4). The funders did not have any role in the study and did not have any authority over any study activity or in the decision to submit the report for publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2020.01.007.

References

Akoglu, H. (2018). User's guide to correlation coefficients. *Turkish Journal of Emergency Medicine, 18*(3), 91–93. https://doi.org/10.1016/j.tjem.2018.08.001.

Bland, M. (2015). Estimating mean and standard deviation from the sample size, three quartiles, minimum, and maximum. *International Journal of Statistics in Medical Research, 4*(1), 57–64. https://doi.org/10.6000/1929-6029.2015.04.01.6.

Bramble, D. M., & Lieberman, D. E. (2004). Endurance running and the evolution of Homo. *Nature, 432*(7015), 345–352. https://doi.org/10.1038/nature03052.

Buldt, A. K., Levinger, P., Murley, G. S., Menz, H. B., Nester, C. J., & Landorf, K. B. (2015). Foot posture is associated with kinematics of the foot during gait: A comparison of normal, planus and cavus feet. *Gait & Posture, 42*(1), 42–48. https://doi.org/10.1016/j.gaitpost.2015.03.004.

Cavanagh, P. R., & Rodgers, M. M. (1987). The arch index: A useful measure from footprints. *Journal of Biomechanics, 20*(5), 547–551. https://doi.org/10.1016/0021-9290(87)90255-7.

Chang, R., Kent-Braun, J. A., & Hamill, J. (2012). Use of MRI for volume estimation of tibialis posterior and plantar intrinsic foot muscles in healthy and chronic plantar fasciitis limbs. *Clinical Biomechanics, 27*(5), 500–505. https://doi.org/10.1016/j.clinbiomech.2011.11.007.

Farris, D. J., Kelly, L. A., Cresswell, A. G., & Lichtwark, G. A. (2019). The functional importance of human foot muscles for bipedal locomotion. *Proceedings of the National Academy of Sciences of the United States of America, 116*(5), 1645–1650. https://doi.org/10.1073/pnas.1812820116.

Ferreira, A. F. B., Laurindo, I. M. M., Rodrigues, P. T., Ferraz, M. B., Kowalski, S. C., & Tanaka, C. (2008 Oct). Brazilian version of the foot health status questionnaire (FHSQ-Br): Cross-cultural adaptation and evaluation of measurement properties. *Clinics, 63*(5), 595–600. https://doi.org/10.1590/S1807-59322008000500005.

Fukano, M., & Fukubayashi, T. (2009). Motion characteristics of the medial and lateral longitudinal arch during landing. *European Journal of Applied Physiology, 105*(3), 387–392. https://doi.org/10.1007/s00421-008-0915-3.

Goldmann, J.-P., Sanno, M., Willwacher, S., Heinrich, K., & Brüggemann, G.-P. (2012). The potential of toe flexor muscles to enhance performance. *Journal of Sports Sciences, 31*, 1–10. https://doi.org/10.1080/02640414.2012.736627 (March 2015).

Haley, S. M., & Fragala-Pinkham, M. A. (2006). Interpreting change scores of tests and measures used in physical therapy. *Physical Therapy, 86*(5), 735–743. https://doi.org/10.1093/ptj/86.5.735.

Hillstrom, H. J., Song, J., Kraszewski, A. P., Hafer, J. F., Mootanah, R., Dufour, A. B., et al. (2013). Foot type biomechanics part 1: Structure and function of the asymptomatic foot. *Gait & Posture, 37*(3), 445–451. https://doi.org/10.1016/j.gaitpost.2012.09.007.

Holowka, N. B., & Lieberman, D. E. (2018). Rethinking the evolution of the human foot: Insights from experimental research. *Journal of Experimental Biology, 221*(17), jeb174425. https://doi.org/10.1242/jeb.174425.

Holowka, N. B., Wallace, I. J., & Lieberman, D. E. (2018). Foot strength and stiffness are related to footwear use in a comparison of minimally- vs. conventionally-shod populations. *Scientific Reports, 8*(1), 3679. https://doi.org/10.1038/s41598-018-21916-7.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics, 21*(1), 31–43. https://doi.org/10.1123/jab.21.1.31.

Kaufman, K. R., Brodine, S. K., Shaffer, R. A., Johnson, C. W., & Cullison, T. R. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. *The American Journal of Sports Medicine, 27*(5), 585–593. https://doi.org/10.1177/03635465990270050701.

Kelly, L. A., Cresswell, A. G., & Farris, D. J. (2018). The energetic behaviour of the human foot across a range of running speeds. *Scientific Reports, 8*(1), 10576. https://doi.org/10.1038/s41598-018-28946-1.

Kelly, L. A., Kuitunen, S., Racinais, S., & Cresswell, A. G. (2012). Recruitment of the plantar intrinsic foot muscles with increasing postural demand. *Clinical Biomechanics, 27*(1), 46–51. https://doi.org/10.1016/j.clinbiomech.2011.07.013.

Kelly, L. A., Lichtwark, G., & Cresswell, A. G. (2015). Active regulation of longitudinal arch compression and recoil during walking and running. *Journal of The Royal Society Interface, 12*(102), 20141076. https://doi.org/10.1098/rsif.2014.1076.

Ker, R. F., Bennett, M. B., Bibby, S. R., Kester, R. C., & Alexander, R. M. (1987). The spring in the arch of the human foot. *Nature, 325*(6100), 147–149. https://doi.org/10.1038/325147a0.

Kim, M. H., Yi, C. H., Weon, J. H., Cynn, H. S., Jung, D. Y., & Kwon, O. Y. (2015). Effect of toe-spread-out exercise on hallux valgus angle and cross-sectional area of abductor hallucis muscle in subjects with hallux valgus. *Journal of Physical Therapy Science, 27*(4), 1019–1022. https://doi.org/10.1589/jpts.27.1019.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*, 863. https://doi.org/10.3389/fpsyg.2013.00863.

Leardini, A., Benedetti, M. G., Berti, L., Bettinelli, D., Nativo, R., & Giannini, S. (2007). Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait & Posture, 25*(3), 453–462. https://doi.org/10.1016/j.gaitpost.2006.05.017.

Lieberman, D. E., Castillo, E. R., Otarola-Castillo, E., Sang, M. K., Sigei, T. K., Ojiambo, R., et al. (2015). Variation in foot strike patterns among habitually barefoot and shod runners in Kenya. *PLoS One, 10*(7), e0131354. https://doi.org/10.1371/journal.pone.0131354.

Lynn, S. K., Padilla, R. a, & Tsang, K. K. W. (2012). Differences in static- and dynamic-balance task performance after 4 weeks of intrinsic-foot-muscle training: The short-foot exercise versus the towel-curl exercise. *Journal of Sport Rehabilitation, 21*(4), 327–333. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/22715143.

Matias, A. B., Taddei, U. T., Duarte, M., & Sacco, I. C. N. (2016). Protocol for evaluating the effects of a therapeutic foot exercise program on injury incidence, foot functionality and biomechanics in long-distance runners: A randomized controlled trial. *BMC Musculoskeletal Disorders, 17*(1), 1–11. https://doi.org/10.1186/s12891-016-1016-9.

Mckeon, P. O., Hertel, J., Bramble, D., & Davis, I. (2014). The foot core system: A new paradigm for understanding intrinsic foot muscle function. *British Journal of Sports Medicine*, 1–9. https://doi.org/10.1136/bjsports-2013-092690.

Mei, Q., Gu, Y., Xiang, L., Baker, J. S., & Fernandez, J. (2019). Foot pronation contributes to altered lower extremity loading after long distance running. *Frontiers in Physiology, 10*, 573. https://doi.org/10.3389/fphys.2019.00573.

Mickle, K. J., Caputi, P., Potter, J. M., & Steele, J. R. (2016). Efficacy of a progressive resistance exercise program to increase toe flexor strength in older people. *Clinical Biomechanics, 40*, 14–19. https://doi.org/10.1016/j.clinbiomech.2016.10.005.

Mickle, K. J., Chambers, S., Steele, J. R., & Munro, B. J. (2008). A novel and reliable method to measure toe flexor strength. *Clinical Biomechanics, 23*(5), 683. https://doi.org/10.1016/j.clinbiomech.2008.03.025.

Mickle, K. J., Munro, B. J., Lord, S. R., Menz, H. B., & Steele, J. R. (2009). ISB clinical biomechanics award 2009. *Clinical Biomechanics, 24*(10), 787–791. https://doi.org/10.1016/j.clinbiomech.2009.08.011.

Miller, E. E., Whitcome, K. K., Lieberman, D. E., Norton, H. L., & Dyer, R. E. (2014). The effect of minimal shoes on arch structure and intrinsic foot muscle strength. *Journal of Sport and Health Science, 3*(2), 74–85. https://doi.org/10.1016/j.jshs.2014.03.011.

Mulligan, E. P., & Cook, P. G. (2013). Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function. *Manual Therapy, 18*(5), 425–430. https://doi.org/10.1016/j.math.2013.02.007.

Munro, C. F., Miller, D. I., & Fuglevand, A. J. (1987). Ground reaction forces in running: A reexamination. *Journal of Biomechanics, 20*(2), 147–155. https://doi.org/10.1016/0021-9290(87)90306-X.

Nigg, B. (2009). Biomechanical considerations on barefoot movement and barefoot shoe concepts. *Footwear Science, 4280*(2), 73–79. https://doi.org/10.1080/19424280903204036.

Oxford Centre for Evidence-based Medicine - Levels of Evidence (March 2009) -

CEBM. (n.d.). Retrieved January 5, 2020, from https://www.cebm.net/2009/06/oxford-centre-evidence-based-medicine-levels-evidence-march-2009/.

Portinaro, N., Leardini, A., Panou, A., Monzani, V., & Caravaggi, P. (2014). Modifying the Rizzoli foot model to improve the diagnosis of pes-planus: Application to kinematics of feet in teenagers. *Journal of Foot and Ankle Research, 7*(1), 1–7. https://doi.org/10.1186/s13047-014-0057-2.

Redmond, A. C., Crane, Y. Z., & Menz, H. B. (2008). Normative values for the foot posture index. *Journal of Foot and Ankle Research, 1*(1), 6. https://doi.org/10.1186/1757-1146-1-6.

Riddick, R., Farris, D. J., & Kelly, L. A. (2019). The foot is more than a spring: Human foot muscles perform work to adapt to the energetic requirements of locomotion. *Journal of The Royal Society Interface, 16*(150), 20180680. https://doi.org/10.1098/rsif.2018.0680.

Ridge, S. T., Myrer, J. W., Olsen, M. T., Jurgensmeier, K., & Johnson, A. W. (2017). Reliability of doming and toe flexion testing to quantify foot muscle strength. *Journal of Foot and Ankle Research, 10*(1), 55. https://doi.org/10.1186/s13047-017-0237-y.

Robbins, S. E., & Hanna, A. M. (1987). Running-related injury prevention through barefoot adaptations. *Medicine & Science in Sports & Exercise, 19*(2), 148–156. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/2883551.

Sawada, T., Tanimoto, K., Tokuda, K., Iwamoto, Y., Ogata, Y., Anan, M., et al. (2017). Rear foot kinematics when wearing lateral wedge insoles and foot alignment influence the effect of knee adduction moment for medial knee osteoarthritis. *Gait & Posture, 57*, 177–181. https://doi.org/10.1016/j.gaitpost.2017.06.009.

Sawada, T., Tokuda, K., Tanimoto, K., Iwamoto, Y., Ogata, Y., Anan, M., et al. (2016). Foot alignments influence the effect of knee adduction moment with lateral wedge insoles during gait. *Gait & Posture, 49*, 451–456. https://doi.org/10.1016/j.gaitpost.2016.08.011.

Son, S. J., Kim, H., Seeley, M. K., & Hopkins, J. T. (2019). Altered walking neuromechanics in patients with chronic ankle instability. *Journal of Athletic Training, 54*(6), 684–697. https://doi.org/10.4085/1062-6050-478-17.

Teng, P. S. P., Kong, P. W., & Leong, K. F. (2017). Effects of foot rotation positions on knee valgus during single-leg drop landing: Implications for ACL injury risk reduction. *The Knee, 24*(3), 547–554. https://doi.org/10.1016/j.knee.2017.01.014.

Unger, C. L., & Wooden, M. J. (2000). Effect of foot intrinsic muscle strength training on jump performance. *14*(4), 373–378.

Winter, D. A., & Patla, A. E. (1997). *Signal processing and linear systems for the movement sciences*. Waterloo Biomechanics. Retrieved from https://books.google.com.br/books/about/Signal_Processing_and_Linear_Systems_for.html?id=33bBAAAACAAJ&redir_esc=y.