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Effects of training in minimalist shoes on the intrinsic and extrinsic foot muscle volume

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ABSTRACT

Background: Minimalist shoes have gained popularity recently because it is speculated to strengthen the foot muscles and foot arches, which may help to resist injuries. However, previous studies provided limited evidence supporting the link between changes in muscle size and footwear transition. Therefore, this study sought to examine the effects of minimalist shoes on the intrinsic and extrinsic foot muscle volume in habitual shod runners. The relationship between participants' compliance with the minimalist shoes and changes in muscle õ-volume was also evaluated.
Methods: Twenty habitual shod runners underwent a 6-month self-monitoring training program designed for minimalist shoe transition. Another 18 characteristics-matched shod runners were also introduced with the same program but they maintained running practice with standard shoes. Runners were monitored using an online surveillance platform during the program. We measured overall intrinsic and extrinsic foot muscle volume before and after the program using MRI scans.
Findings: Runners in the experimental group exhibited significantly larger leg ($P = 0.01$, Cohen's d = 0.62) and foot ($P < 0.01$, Cohen's d = 0.54) muscle after transition. Foot muscle growth was mainly contributed by the forefoot ($P < 0.01$, Cohen's d = 0.64) but not the rearfoot muscle ($P = 0.10$, Cohen's d = 0.30). Leg and foot muscle volume of runners in the control group remained similar after the program ($P = 0.33$–0.95). A significant positive correlation was found between participants' compliance with the minimalist shoes and changes in leg muscle volume ($r = 0.51$; $P = 0.02$).
Interpretation: Habitual shod runners who transitioned to minimalist shoes demonstrated significant increase in leg and foot muscle volume. Additionally, the increase in leg muscle volume was significantly correlated associated with the compliance of minimalist shoe use.

1. Introduction

Running is one of the most popular forms of physical activity and it has been reported to promote cardiopulmonary and musculoskeletal fitness, as well as psychological health (Guten, 1997). However, due to its repetitive nature, overuse injuries in running are common, with 37–79% of runners sustaining an injury in a given year (van Gent et al., 2007). Interestingly, sophisticated footwear design and shoe prescription do not reduce running injury (Knapik et al., 2014). The anecdotal evidence (McDougall, 2010) along with the scientific findings (Lieberman et al., 2010) on the potential health benefits of barefoot running have led to an increasing number of modern-day runners attempting to run barefoot. As a result, minimalist running shoes (MRS), which aim to simulate barefoot running (Squadrone and Gallozzi, 2009), lead to a bloom of new products released in the running shoe market for the past few years (Davis, 2014). MRS generally features flexible upper, less heel–toe drop and minimal cushioning, which is anticipated to impose less restriction for foot motion during running (Squadrone et al., 2014). Due to the removal of arch support and cushioning, MRS was reported to cause running injuries e.g. stress fracture and tendonitis in habitual shod runners undergoing the transition (Goss and Gross, 2012; Ridge et al., 2013; Salzler et al., 2012). However, MRS are also incorporated in other clinical applications such as knee osteoarthritis due to their purported therapeutic effects in improving musculoskeletal function (Trombini-Souza et al., 2012).

Traditional running shoes (TRS) have arch support which is designed to reduce the demand on the arch musculature. While there is no evidence that these shoe features actually support the arch, the use of MRS is speculated to improve intrinsic foot muscle (IFM) and extrinsic foot muscle (EFM) strength by providing less mechanical support to the foot arches (Bruggemann et al., 2005; Johnson et al., 2015; Miller et al., 2014). It has been reported that the anatomical cross-sectional

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area of selected IFMs and EFMs was increased by 4–5% in athletes using MRS during athletes preparatory training (Bruggemann et al., 2005). Strength of the metatarsophalangeal joint flexors, ankle plantar flexors, and dorsi flexors was also increased significantly after intervention. A recent prospective study echoed these findings by exploring the effects of running in MRS on the IFM (Miller et al., 2014). The results indicated that MRS running increased muscle volume of both flexor digitorum brevis and abductor digiti minimi.

It has been well accepted that both IFM and EFM are critical structures in stabilizing the foot arches (Headlee et al., 2008; Jam, 2006; O'Connor and Hamill, 2004). Weakness of IFM and EFM has been associated with running injuries, such as plantar fasciitis (Chang et al., 2012; Cheung et al., 2015). Theoretically, strengthening of IFM and EFM could be achieved by MRS as it increased the demand of active support for the foot arches. Preliminary evidence supported the positive effects of MRS on the foot muscle strength (Bruggemann et al., 2005; Johnson et al., 2015; Miller et al., 2014). However, some weaknesses of previous studies may compromise the generalization of the findings. First of all, anatomical cross-sectional area has limitations as a surrogate of muscle strength due to the variability in muscle geometry among individuals (Fukunaga et al., 2001). Instead, muscle strength is directly related ($r = 0.61–0.89$) to its volume (Fukunaga et al., 2001). Additionally, participants in the study by Bruggemann and colleagues only used MRS during warm-up exercise and whether they had habituated MRS was questionable. In the study by Miller and colleagues, they only investigated three selected IFMs in their study but the effect of MRS on EFMs remains unclear (Johnson et al., 2015; Miller et al., 2014).

Magnetic resonance imaging (MRI) has become a sophisticated technique to measure muscle geometry through three-dimensional modeling (Bamman et al., 2000; Im et al., 2014; Popadic Gacesa et al., 2009). Compared to other methods, MRI has high spatial resolution, direct in-vivo assessment and it is non-invasive (Bus et al., 2009; Kuo and Carrino, 2007). At the same time MRI provides a good reliability (Intraclass correlation coefficient ranged from 0.96 to 0.99) in the muscle volume measurement for both IFM and EFM (Barnouin et al., 2014; Commean et al., 2011; Smeulders et al., 2010).

Therefore, this study sought to examine the effect of MRS on the IFM and EFM volume in habitual shod runners. We also evaluated the relationship between participants' compliance with MRS and their corresponding change in the IFM and EFM volume. We hypothesized that both IFM and EFM volume would be greater in habitual shod runners who transitioned from TRS to MRS. We also expected a positive correlation between participant's MRS compliance and their muscle growth.

2. Methods

2.1. Study design and setting

This study was a randomized, single-blinded, controlled trial. Prior to the experiment, eligible participants were fully informed of the research procedures and signed an informed consent form. The study protocol was reviewed and approved by the concerning institutional review board.

2.2. Eligibility criteria

Habitual shod (ran with TRS during their regular running training and never attempted barefoot running or running with MRS) runners (≥ 20 km/week for ≥ 12 months) aged between 20 and 45 were recruited from local running clubs. We operationally defined TRS as footwear of heel-toe drop >5 mm, with additional cushioning padding and artificial arch support (Rixe et al., 2012). Participants were excluded if they had any active musculoskeletal injury or known cardiopulmonary conditions. Those who had contraindications to MRI were also excluded.

2.3. Randomization

Participants were randomly allocated to one of the two study groups by opening a sealed envelope, which was prepared beforehand and contained a number generated by a random allocation program. An independent researcher who was blinded to recruitment performed the randomization and provided the authors with assignment results.

2.4. Intervention

Runners in the experimental group underwent a six-month training program aiming to help habitual shod runners adapt to MRS. At the beginning of the program, each participant was given a pair of MRS (Vibram FiveFingers, Vibram, Albizzate, Italy) and a self-monitoring program comprising transition exercise regimens (calf strengthening exercise, balance training, and foot placement drills) and transitioning tips (Spaulding National Running Center, 2016). The MRS that we used in this study featured an open-topped upper made of stretch fabric, five separated toe compartments, zero heel-to-toe drop, no midsole cushioning or arch support, and a uniform 3 mm outer sole (Vibram FiveFingers, 2016). According to a rating scale for minimalist shoes published recently (Esculier et al., 2015), the total minimalist index score of this MRS was 92%, indicating a good degree of minimalism. Runners in the control group also received the same training program but they were asked to conduct the exercise and continue running with their own TRS. During the training, participants of both groups were required to report their monthly running mileage, footwear usage, and usual pacing through an online surveillance platform. Participants' compliance with MRS was evaluated by dividing the mileage that participants finished with MRS by the total mileage during the six-month training. As such 100% indicated a complete compliance with the MRS during the training while 0% referred to a non-compliant participant, who did not run with MRS during the program.

2.5. Assessments

At the baseline and the end of the 6-month intervention, all the participants were invited to undergo a MRI scanning of their right leg and foot. A 1.5-T magnet was used to acquire T1-weighted spin-echo series of images (repetition time = 500 ms; echo time = 16 ms; averages = 3; slice thickness = 4 mm; gap = 0 mm; field of view = 120×120 mm; flip angle = 90°; matrix = 512×512). Each participant was required to lay supine with the foot or leg inserted into a circular polarized head coil. In a position at 30° plantar flexion, the foot was imaged in a sagittal and frontal plane view, and the leg was imaged in a transverse plane view. We adopted the algorithm for muscle volume measurement from a previous study (Chang et al., 2012). In brief, the MRI images were imported into Mimics (Materialise, Leuven, Belgium) and the muscles of interests were segmented by excluding all non-contractile tissues such as bone, fat, connective tissue, nerve, and blood vessels. Volumes were then computed by summing the product of slice thickness and the muscle cross-sectional area for each image. EFMs were calculated by identifying all muscles lying in the region below the knee joint center and above the lateral malleoli level, while IFMs referred to those distributed in the foot area. Rearfoot and forefoot segments were defined by splitting the total number of images containing muscle into anterior half and posterior half of the foot (Chang et al., 2012; Cheung et al., 2015), respectively. The inter-session reliability of this imaging processing method was examined in a previous study (Cheung et al., 2015) and the coefficients of variance for IFM and EFM were 1.3% and 1.7% respectively. In order to eliminate the effects of variances in individual anthropometry, as well as for direct comparison between previous findings, muscle volume was normalized by participants' body mass.

2.6. Blinding

All participants were blinded to the null hypothesis concerning which one of the two groups was preferred. Runners were unaware of the existence of the other study group by undergoing the training individually. The researcher who measured the muscle volume was also blinded to the group allocation.

2.7. Statistical analyses

Baseline characteristics were compared between the experimental and control groups using independent Student t tests. Analysis of gender was carried out by chi-square test. Muscle volume of the leg, foot, rearfoot and forefoot was compared using paired Student t tests. In addition, in order to avoid overreliance on statistical tests (Nuzzo, 2014), the effect size (Cohen's d) was calculated using PASS (version 13, NCSS Statistical Software, Kaysville, UT, USA). Pearson's coefficient was used to measure the correlation between participant's MRS compliance and change in muscle volume after transition in the experimental group. Global alpha was set at 0.05.

3. Results

3.1. Participants

A total of 55 participants were assessed for eligibility, 8 of them were excluded (Fig. 1). Among 47 eligible runners, 23 were randomized to the control group and 24 to the experimental group. After 6-month training, 9 runners dropped out because of scheduling conflicts ($n = 8$) and loss of contact ($n = 1$). Data from 38 runners (18 controls, 20 experimental) were analyzed. Table 1 summarizes the characteristics of the enlisted participants in both study groups. Their demographics, running experience, usual pacing (pre- and post-training), and weekly mileage (pre- and post-training) were comparable.

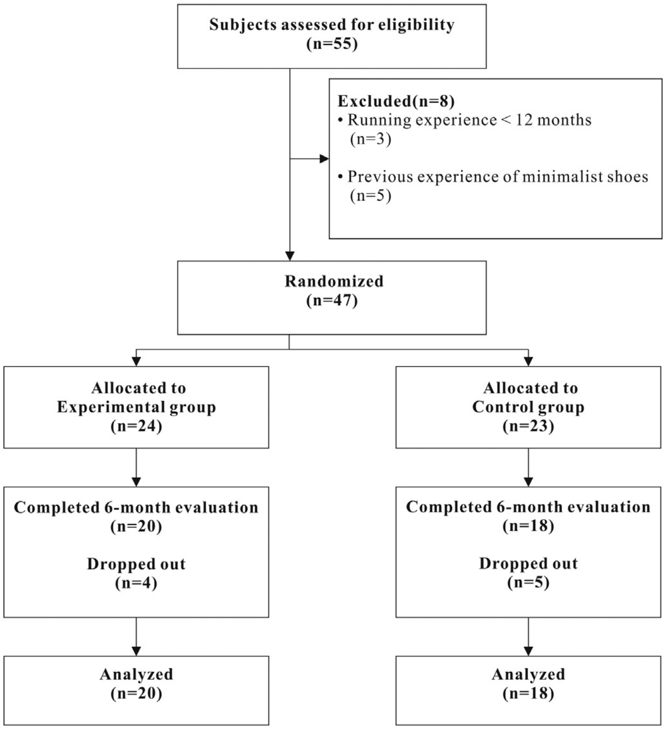

Fig. 1. CONSORT flow diagram.

Table 1
Characteristics of the participants.

Group		TRS group	MRS group	*P*-value
		Mean (SD)	Mean (SD)	
Gender		10 males, 8 females	11 males, 9 females	0.97
Age (year)		35.00 (5.39)	34.55 (6.62)	0.82
Mass (kg)		61.77 (9.57)	61.50 (10.26)	0.93
Height (m)		1.66 (0.09)	1.66 (0.10)	0.97
Experience (year)		5.50 (5.56)	6.12 (4.80)	0.72
Usual pacing (min/km)	Pre-training	5.83 (1.04)	5.45 (0.99)	0.26
	Post-training	5.99 (1.15)	5.72 (1.07)	0.55
Week mileage (km)	Pre-training	35.02 (21.34)	26.32 (21.24)	0.22
	Post-training	33.87 (22.51)	28.00 (15.29)	0.61

3.2. Outcomes

3.2.1. Muscle volume

Participants in the experimental group exhibited significantly greater EFM ($P = 0.01$, increased by 7.05%, Cohen's $d = 0.62$) and IFM ($P < 0.01$, increased by 8.80%, Cohen's $d = 0.54$) volume after MRS transition (Table 2). Foot muscle hypertrophy was attributed more to the forefoot ($P < 0.01$, Cohen's $d = 0.64$) than the rearfoot volume ($P = 0.10$, Cohen's $d = 0.30$). In contrast, the volume of IFM and EFM in the control group remained unchanged ($P = 0.33$–0.95, Cohen's $d = -0.08$ to 0.21).

3.2.2. Compliance

Participants in the experimental group reported a large range of compliance with MRS (average compliance = 39.2% SD 27.0). We found a significant positive correlation between participants' MRS compliance and the changes in leg muscle volume ($r = 0.51$; $P = 0.02$). A similar trend was observed between the MRS compliance and foot muscle increase, but it was statistically non-significant ($r = 0.39$; $P = 0.09$).

4. Discussion

In the present study, MRI scanning was used to obtain an accurate measurement of the IFM and EFM volume. As we expected, a six-month transition program was effective in promoting muscle growth of both IFM and EFM. Leg muscle volume increase was shown to be associated with participants' compliance with MRS.

Similar to Bruggemann et al. (2005); Miller et al. (2014), and Johnson et al. (2015), we found chronic MRS use led to increasing volume of the IFM and EFM. As MRS provides minimal cushioning and no mechanical support to the foot arches, we expected the IFM and EFM, which function as important foot arch stabilizers, would experience greater demands upon them. The volumetric growth of EFM may also be due to higher strain and greater force generation in the posterior and medial calf muscles when running with MRS (Perl et al., 2012). However, these findings were in conflict with some indirect evidence regarding footwear in runners. A study using EMG-driven model to predict muscle strength (Rao et al., 2015) demonstrated no significant differences in maximal activation and maximal force of the triceps surae and the tibialis anterior between MRS and TRS. Increase in the EMG could reflect the enhancement in neuromuscular activity stimulated and it was related to muscle hypertrophy during strength training (Cannon et al., 2007; Häkkinen et al., 2001). However, in the present study, we tested the effect of habitual MRS use on muscle size, while Rao et al. (2015) only tested their immediate response of MRS. Since habitual shod runners may not mechanically behave the same with barefoot running upon initial exposure to MRS running (Cheung and Rainbow, 2014; Valenzuela et al., 2015; Willy and Davis, 2014), this discrepancy might be expected.

Table 2
Comparisons of muscle volume.

Group		Pre-training	Post-training	Cohen's d	*P*-value
		Mean (SD)	Mean (SD)		
TRS group (mm^3/kg)	Leg	27,634.23 (2532.26)	27,425.54 (2463.83)	−0.08	0.59
	Foot	4613.94 (723.98)	4739.53 (941.34)	0.15	0.38
	Rearfoot	2526.27 (485.81)	2647.36 (660.84)	0.21	0.33
	Forefoot	2087.66 (333.13)	2092.16 (330.48)	0.02	0.95
MRS group (mm^3/kg)	Leg	25,082.47 (2786.17)	27,031.84 (3448.16)	0.62	0.01
	Foot	4566.96 (753.51)	4973.51 (766.50)	0.54	<0.01
	Rearfoot	2592.21 (630.42)	2764.32 (531.33)	0.30	0.10
	Forefoot	1974.27 (303.23)	2209.64 (417.21)	0.64	<0.01

In our study, runners in the experimental group exhibited approximately 7–9% volumetric increase of the IFM and EFM. This change was slightly greater than that reported by Johnson et al. (2015) (no significant changes in all IFM volume except for the abductor hallucis) and Bruggemann et al. (2005) (approximately 4–5%). This may be explained by the longer and more systematic transition program used in the current study. Miller et al. (2014) reported an even greater increase (approximately 17%–24%). However, they assessed individual muscles compared to groups of muscles as in our study. When grouping muscles in to the rearfoot and forefoot regions, we found muscle increases of 6.6% and 11.9% respectively. According to previous studies (Chang et al., 2012; Cheung et al., 2015), the majority of the forefoot muscles were responsible for generating plantar flexion moment at the first metatarsophalangeal joint, indicating that IFM were critical in controlling the medial longitudinal arch flattening in weight bearing. Atrophy of IFM elevated the plantar fascia strain and the risks of plantar fasciitis (Chang et al., 2012; Cheung et al., 2015). In spite of that, weak foot muscle strength has been associated with other running injuries (Azevedo et al., 2009; Fong et al., 2009; Soysa et al., 2012). There is a trend among clinicians and sports scientists to encourage the use of MRS among runners as a mean to reduce injury (Tam et al., 2014). Since the causative relationship between foot muscle atrophy and the development of these injuries remains unclear, it is still uncertain whether MRS would be beneficial or detrimental and further research is needed to substantiate the therapeutic effects of MRS. According to a recent paradigm (McKeon et al., 2015), IFM and EFM were the functional muscular components constituting the foot core system, which was a complex anatomical structures that stabilized the foot arch. Unlike EFM, IFM featured multilayer small muscles that provided intersegmental stability. They were the primary local arch stabilizers that controlled the degree of gross motion generated by EFM during locomotion. Atrophy of IFM resulted in abnormal movement of the foot core system in accommodating to changing loading demands and led to injury. Our study showed that the transition to MRS strengthened the muscular components of the foot core system, indicating its potential application in rehabilitation program. Instead of focusing on foot orthotic device, foot core training should receive more attention in current clinical guidelines in treating injury related to weak foot muscles.

There are many transition programs that are currently available (Kernozek et al., 2014; McCarthy et al., 2013; Ridge et al., 2013; Warne et al., 2014). While the details of these programs are different, participants are generally required to progressively increase their mileage while transitioning to MRS. Compared to those available protocols, our training period was apparently longer (6 months versus 4–12 weeks), which allowed runners to progress more slowly and for muscle growth to occur. Like others, we provided the participants with an additional exercise regimen. The exercise frequency used in our study was similar to that of McCarthy et al. (2013) (3 days per week). However, we imposed higher intensity of calf strengthening (30 versus 15 repetitions for each set) and more holistic balance training (dynamic trials versus static single leg balance). In the present study, we had no runners experiencing transition-related injuries. This is in contrast with results from a previous study (Ridge et al., 2013). In this study a self-monitoring transition program, adopted from the website (Vibram FiveFingers, 2016) was applied. Foot muscle strengthening exercise ceased after the third week of training. Subjects began running with MRS immediately at the onset of training and increased mileage by approximately 25–50% during the first three weeks. Compared to our study, the Ridge et al. transition program progressed more aggressively and may not incorporate sufficient exercise into the running routines. Those authors reported that 10 of 19 runners demonstrated bony edema via MRI at the end of a 10-week training for transition. Likewise, 8 out of 18 runners developed bone marrow edema in Johnson's study in which a similar training strategy was employed (Johnson et al., 2015). These factors may result in the high injury incidences in their study. It should be noted that most of these runners with bony edema were asymptomatic, underscoring the subclinical nature of these bony injuries. As we did not obtain MRI of our runners initially, we do not know if bony edema was present in them.

While there was no subject attrition related to transition-related injuries in our study, there was a wide range of MRS compliance among runners in the experimental group. This might be due to the way we calculated compliance. We estimated the compliance by dividing the mileage that participants ran in MRS by the total mileage during the six-month training. However, a few participants reported that they did not want to cut the usual mileage and remained training with TRS during transition. Therefore, some runners ran more in their MRS, but ran less miles, while others ran more miles, but less in their MRS.

MRS compliance was significantly correlated with the EFM volume growth, but not with IFM growth. It is highly possible that MRS running imposed more stimuli on EFM because of the greater loading of the gastrocnemius (Biewener and Daley, 2007). Although IFM and EFM both support the foot arches, EFMs are also critical ankle joint stabilizers (O'Connor and Hamill, 2004; Sherman, 1999). While we did not examine the footstrike pattern of our runners, it has been shown that runners tend to land with midfoot or forefoot strike pattern with MRS (De Wit et al., 2000; Lieberman et al., 2010). This strike pattern is associated with greater work of the calf musculature (Hamill et al., 2014). Therefore, it is not surprising that the volumetric growth of EFM was correlated with the usage of MRS. Interestingly, we found that IFM growth in the experimental group was mainly due to the forefoot muscles. Mid/forefoot landing imposed more stimuli to the anterior part of the foot, especially for the metatarsophalangeal joint (Liebl et al., 2014). Therefore, muscles responsible for metatarsophalangeal joint motions may be more strengthened with this type of landing (Chang et al., 2012). Our findings suggested that approximately 25% of the variance in the changes of leg muscle volume could be explained by runners' compliance to MRS. Our training involving muscle strengthening was not mandatory at the later stage of the program. Since we only measured the compliance of footwear use but not the exercise regimen, the exercise intensity during the training was uncertain and it may explain the unchanged muscle volume in the TRS group. Finally, runners had the MRI scan immediately after the training. Water retention or inflammation may also attribute to the muscle volume increment (Chang et al., 2012).

While the main focus of previous studies has been on the potential biomechanical advantages of MRS in runners, the present study addressed the issue from a different perspective. Our findings have substantiated the relationship between MRS and muscle hypertrophy in the IFM and EFM. These findings will hopefully provide a better understanding of the clinical effects of MRS. As muscle growth is induced by MRS, they can be used as an intervention for foot problems related to the weakness of IFM and EFM. For example, Ryan et al. (2009) has demonstrated that the use of MRS provides additional benefits to a group of patients with plantar fasciitis undergoing a standardized exercise program (Ryan et al., 2009). All of our participants had a successful transition in six months and they were able to return to their previous running mileage. However, transitions to minimal footwear without proper preparation and a slow progression can result in injury. Salzler et al. reported on a case series of injuries associated with transition to minimal shoes. However, the average transition time was only 3 weeks (Salzler et al., 2012). It is expected that shod runners might not have sufficient IFM and EFM strength to cope with MRS at the early stage of transition. We believe that the training regimen, training intensity, and pace of the transition program are key elements to a successful transition.

There were several limitations of this study. First, there was a large range of compliance with MRS among participants in the experiment group. Given its significant correlation with changes in muscle volume, the overall effects of MRS were inevitably compromised. In addition, the whole training program was monitored through an online surveillance platform. Participants' reports on their progression may not be completely validated. The effects of compliance to MRS may be underestimated by forgetting to report. Secondly, we did not investigate individual foot muscle volume in the present study. In order to identify individual muscle volume from MRI scans, a better MRI resolution is needed but it would significantly lengthen the scanning duration to nearly 2 h. This was not practical for most of the participants. Therefore, we adopted the protocol used in the previous studies and referred to the method that grouped foot muscles according to their anatomic location. Finally, there are different kinds of MRS available in the market. Different MRS designs may influence its effects on the IFM and EFM. However, this issue could not be addressed in our study. Also, it was reported that habitual shod runners tended to adopt a non-rearfoot landing when using MRS (Squadrone et al., 2014; Warne et al., 2014), which may also cause some neuromuscular adaptations. However, we did not measure the landing pattern before and after the transitioning in the present study.

5. Conclusions

Habitual shod runners demonstrated volumetric increases in the intrinsic and extrinsic foot muscle volume after a six-month minimalist shoes transition program. The changes in the leg muscle volume were associated with runners' compliance with the minimalist shoes.

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