



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 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 on-line 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.

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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 EFM 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 ($r = 0.61\text{--}0.89$) 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 EFM 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. EFM 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.

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