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Walking in Minimalist Shoes Is Effective for Strengthening Foot Muscles

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Abstract

Introduction: Weakness of foot muscles may contribute to a variety of loading-related injuries. Supportive footwear may contribute to intrinsic foot muscle weakness by reducing the muscles' role in locomotion (e.g., absorbing forces and controlling motion). Increased stimulus to the foot muscles can be provided through a variety of mechanisms, including minimalist footwear and directed exercise.

Purpose: To determine the effect of walking in minimalist footwear or performing foot strengthening exercises on foot muscle size and strength.

Methods: Fifty-seven runners were randomly assigned to one of three groups—minimalist shoe walking (MSW), foot strengthening (FS) exercise, or control (C). All groups maintained their pre-study running mileage throughout the study. The MSW group walked in provided footwear, increasing weekly the number of steps per day taken in the shoes. The FS group performed a set of progressive resistance exercises at least 5 d·wk⁻¹. Foot muscle strength (via custom dynamometers) and size (via ultrasound) were measured at the beginning (week 0), middle (week 4), and end (week 8) of the study. Mixed model ANOVA were run to determine if the interventions had differing effects on the groups.

Results: There were significant group–time interactions for all muscle size and strength measurements. All muscle sizes and strength increased significantly from weeks 0 to 8 in the FS and MSW groups, whereas there were no changes in the C group. Some muscles increased in size by week 4 in the FS and MSW groups.

Conclusions: Minimalist shoe walking is as effective as foot strengthening exercises in increasing foot muscle size and strength. The convenience of changing footwear rather than performing specific exercises may result in greater compliance.

Keywords: Foot Muscle Strength, Foot Muscle Size, Minimal Footwear, Foot Strengthening Exercises

The foot is a complex structure with its 26 bones, 33 articulations (each with 6 degrees of freedom of motion) and its 20+ muscles including four layers of arch muscles. This structure allows the foot to serve many different functions, such as providing a base of support, serving as a shock attenuator, being able to adapt to uneven terrain, and serving as a rigid lever for push off (1). The intrinsic muscles of the arch, with their small cross-sectional areas (CSA) and short moment arms are primarily stabilizers, in contrast to the larger extrinsic foot muscles. These intrinsic arch muscles have been referred to as the foot core (1), because they are analogous to the small muscles of the lumbopelvic core that provide stability to the hip and pelvis regions.

Weakness of the intrinsic foot muscles has been associated with loading-related injuries (2–6). These muscles contract with every footstep to control the magnitude and velocity of the downward deflection of the arch (7). The plantar fascia also prevents this deflection (8) and undergoes strain as the arch deflects downward. Weakness of the intrinsic muscles of the arch can lead to a greater deflection and/or velocity of deflection of the arch, placing increased strain on the plantar fascia (3, 9). With the repetitive nature of walking (over 2000 steps per mile), this can easily accumulate into an overuse injury and may explain, in part, the high lifetime incidence (10% of population) of plantar fasciitis reported today (10).

Muscles also provide a balance of forces around bones resulting in a healthy strain environment. For example, Milgrom et al. reported increased tibial bone strain upon fatigue of the lower leg muscles, which may be a major factor in the development of stress fractures (11). Although their study was focused on the tibia, the results are also likely applicable to the bones of the feet. In particular, the metatarsals are at risk as they undergo high bending moments and inherently have low resistance to bending due to their geometry (12, 13). Therefore, strong foot muscles may help to resist this bending and reduce the risk of bone stress injuries.

Foot muscle strengthening is often a component of injury prevention and treatment programs in healthy and pathological populations (6, 14–17). Although strengthening of the long toe flexors is often a component of these programs, targeted contraction of the arch musculature to maintain an arch (i.e., foot doming/short foot exercise) is not as well used in strengthening programs. There is increasing evidence to suggest that training the foot muscles via doming exercises reduces excessive flattening of the arch (18, 19). One study reported 4 wk of foot doming training in healthy individuals reduced navicular drop and increased the arch height index during weight bearing (18). In healthy young adults with pes planus, there were significant increases in great toe (GT) flexion strength and the CSA of the abductor hallucis (ABDH) muscle after 4 wk of doming exercises and foot orthotic intervention compared with foot orthotic intervention alone (19). Minimalist footwear use during running has also been associated with strengthening the intrinsic foot muscles. Several recent studies have assessed the intrinsic foot muscles in runners following transition programs to minimalist footwear compared with runners in conventional footwear (20–22). These studies have reported increased CSA and/or muscle volumes of some of the intrinsic foot muscles in as few as 10 wk (22). Miller et al. (20) also noted an increase in the arch stiffness (i.e., less deformation) during gait. However, there are bone stress injury risks associated with transitioning to running in minimalist footwear too rapidly (23). Walking in minimalist footwear may provide sufficient load to strengthen foot muscles resulting in lower injury risk,

but this has not yet been examined.

Strengthening the foot muscles either through walking in minimalist footwear or targeted exercise may improve foot function and decrease risk of injury. Therefore, the purpose of this study was to measure the changes in intrinsic muscle strength and size in either a footwear or a strengthening intervention. It was hypothesized that minimalist footwear use and foot strengthening would both result in greater strength and size of the foot muscles by 8 wk of intervention.

Methods

Subjects. Subjects were experienced runners between the ages of 18 to 34 yr. Inclusion criteria consisted of an average running mileage between 15 and 30 miles each week for at least 6 months before study participation. Subjects were excluded if they had any lower extremity injuries within the 3 months before beginning the study or if they had run barefoot or in minimalist shoes more than three times within the previous 3 months. A health evaluation screening form was used to verify inclusion criteria.

A total of 65 participants were recruited and randomly assigned to one of three groups: minimalist shoe walking (MSW), foot strengthening (FS) exercise, and control (C). Each subject signed an informed consent document approved by the Human Subjects Review Board at Brigham Young University. Eight participants dropped out of the study due to the time commitment ($n = 4$) or injury unrelated to the study ($n = 4$). Participant demographics for the 57 participants that completed the study are detailed in Table 1. An *a priori* power analysis was run on muscle size changes from a previously published study (22). An expected change of 0.3 cm² with a power of 80% resulted in a sample size of 16 subjects per group.

TABLE 1. Subject demographics.

FS		MSW	Control	All
Age	22 ± 1.8	22.9 ± 3.3	22.6 ± 2.7	22.5 ± 2.7
Height	175.2 ± 8.9	173.5 ± 9.3	173.2 ± 10.9	173.9 ± 11.9
Weight	69.4 ± 11.1	68.6 ± 10.9	69.5 ± 13.3	69.1 ± 11.9
Sex	10 M, 9 F	9 M, 10 F	11 M, 8 F	30 M, 27 F

M, male; F, female.

Intervention. All runners, regardless of group assignment, maintained their pre-study mileage in traditional running shoes throughout their participation in the study. The MSW and FS groups included additional interventions. Participants assigned to the MSW group were given a pair of minimalist shoes (Inov-8 Bare XF 210 or 260) to wear in place of their typical daily footwear and a pedometer (Omron HJ-720ITFFP). Both shoe styles were zero drop with no midsole, differing only by the closure (the XF 210 had elastic laces, whereas the XF 260 had Velcro which resulted in an additional 50 g of weight). Over an 8-wk period, they gradually increased the number of walking steps they took in the minimalist footwear while reducing the number of steps taken in their typical footwear to maintain typical daily activity. Beginning with weeks 1 to 2, participants walked 2500 steps per day in the minimalist shoes.

Weeks 3 to 4 increased to a daily step count of 5000, and ultimately ended weeks 5 to 8 walking 7000 steps daily. Participants were asked to achieve the step count at least 5 d·wk⁻¹. At no time during the study were participants allowed to run in the minimalist shoes. Participants assigned to the FS group were taught a series of exercises developed at the Spaulding National Running Center designed to strengthen their intrinsic and extrinsic foot muscles (Table 2). Each week, they performed these exercises at least 5 d·wk⁻¹—once in the laboratory and four times at home. In accordance with progressive resistance exercises, new variations of the exercises were taught at weekly laboratory visits. Running mileage was recorded by all participants in an online form. Steps taken in minimalist footwear or exercise adherence was recorded on the same online form for the MSW and FS groups, respectively.

TABLE 2. Foot strength group intervention: daily foot/ankle exercises and stretching instructions.

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Double leg heel raises on flat surface	3 sets of 10 to 3 sets of 20	3 sets of 20 to 3 sets of 30						
Double leg heel raises off edge of step			3 sets of 10 to 3 sets of 20	3 sets of 20 to 3 sets of 30				
Single leg heel raises on flat surface					3 sets of 10 to 3 sets of 20	3 sets of 20 to 3 sets of 30		
Single leg heel raises off edge of step							3 sets of 10 to 3 sets of 20 3 sets of 30	3 sets of 20 to 3 sets of 30 3 sets of 30
Towel curls	3 sets of 10 to 3 sets of 20	3 sets of 20	3 sets of 20 to 3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30
Toe spread	3 sets of 10 to 3 sets of 20	3 sets of 20	3 sets of 20 to 3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30
Toe squeeze	3 sets of 10 to 3 sets of 20	3 sets of 20	3 sets of 20 to 3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30
Doming	3 sets of 10 to 3 sets of 20	3 sets of 20	3 sets of 20 to 3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30	3 sets of 30
Doming hopping in place		3 sets of 10	3 sets of 20					
Doming hopping square			3 sets of 20 3 sets of 10 forward and back	3 sets of 20 forward and back	3 sets of 10 side to side	3 sets of 20 side to side	3 sets of 10 diagonal and back	3 sets of 20 diagonal and back

Stretch feet before and after each session. Sitting with one leg crossed over the other, point your foot and stretch your toes into flexion. Hold for 5 s and repeat five times. Then pull your ankle back and your toes back stretching your arch. Hold for 5 s and repeat five times. Move each of your 5 long foot bones with respect to each other.

Data Collection.

All participants met with investigators before beginning the study to sign an informed consent which was approved by Brigham Young University's Human Subjects Review Board. During that visit, they also filled out the health history form and a questionnaire to confirm that they met the inclusion criteria for the study. They were also taught how to perform the doming movement strength test (see below) to decrease the learning effect of performing a novel movement during the first day of testing.

Ultrasound imaging and strength testing were completed at the beginning of the study (week 0), and at the end of weeks 4 and 8. Ultrasound imaging was always completed first, to mitigate any acute effects the strength testing might have on the imaging results.

Imaging of the intrinsic and extrinsic foot muscles was performed by a single trained researcher (9 yr imaging experience) who was blinded to group assignment throughout the data collection. Ultrasound images were collected at a frequency of 10 to 12 MHz using a GE LogiqP6 ultrasound unit (GE Healthcare, USA) with a multilinear array soundhead (ML6—15 MHz). Intratester reliability for the researcher was measured before collection and found to be high (ICC, 0.98–0.99, SEM = 0.003–0.015 cm²; 0.014–0.015 cm), consistent with other similar reported studies (24–26). The CSA or thicknesses of seven muscles were measured for each participant's right foot.

Four intrinsic foot muscles (the flexor hallucis brevis [FHB]), the ABDH, flexor digitorum

brevis [FDB], and quadratus plantae [QP]) were imaged while the subject sat in a semireclined position with the knee supported on a pillow. The hip was abducted and externally rotated, the knee flexed to 90° and the ankle plantarflexed to 30°, allowing access to the plantar surface of the foot. The image of the FHB was recorded by aligning the probe with the shaft of the first metatarsal, using the head of the metatarsal as a bony landmark (Fig. 1). Once the shaft and head of the first metatarsal were visualized concurrently with tendon of the flexor hallucis longus (FHL), the image was recorded. The thickness of the FHB was measured, perpendicularly to the FHL tendon, at 2 cm from the first metatarsal head between the outer border of FHL tendon and the shaft of the first metatarsal (Fig. 1). The CSA of the ABDH was assessed transversely across the medial border of the foot aligned with the navicular tuberosity to ensure repeatability of the ABDH measurement. (Fig. 1). After imaging the ABDH the probe was slid to the plantar surface of the foot and perpendicular to the sole of the foot while maintaining probe alignment with the navicular tuberosity, until the full CSA of the FDB and QP were visualized (Fig. 1). The subject was asked to contract these muscles by gently flexing the toes and then returning to rest. A retrospective cine-loop was recorded, from which still images were selected for measurement purposes. The cine-loop provided a way to help determine fascia borders of FDB and QP for the later measurement of muscle CSA.

To image the extrinsic lower leg muscles (tibialis anterior [TA], tibialis posterior [TP], and FDL), the leg was extended and the thigh was supported on a pillow with the knee slightly flexed thus unweighting the subject's calf. The CSA of the FDL was measured with the ultrasound probe held transversely at a distance of 50% from the medial knee joint line to medial malleolus. The subject was again asked to gently flex the toes to visualize the borders of the FDL fascia. The thicknesses of the TA and TP were measured at 30% of the distance from the lateral knee joint line to the lateral malleolus with the ultrasound probe positioned transversely to the leg. First, the TA was visualized with sufficient gel and light pressure to limit variability in the measurement due to compressing the superficial muscle (Fig. 1). Next, the deeper TP was visualized deep to the interosseous membrane. The subjects were asked to gently invert their foot and then to relax to produce contraction of the TP and help with visualization of the fascial borders of the muscle. This contraction was record with a cine-loop for later analysis. Images were captured when the interosseus membrane appeared horizontal across the ultrasound monitor (Fig. 1). Ultrasound measurements were performed by a separate researcher who was also blinded to group assignment. The manufacturer supplied ultrasound software was used to measure CSA or thickness for each muscle. Measurements from the two recorded images for each muscle were then averaged for statistical analysis.

Strength testing. Three measures of foot muscle strength were collected: GT, lateral toes (LT) flexion, and doming. All measurements were conducted on custom-built apparatuses using reliable techniques (GT ICC, 0.903; GT SEM, 0.703 kg; LT ICC, 0.924; LT SEM, 0.655 kg; doming ICC, 0.949; doming SEM, 0.883 kg) (27). The apparatuses and data collection procedures were described in detail previously (27). To ensure repeatable foot placement and alignment with the dynamometer used for toe flexion, during the first day of testing, each subject's foot was traced onto a piece of paper which rested on top of the platform. During subsequent testing sessions, the foot was realigned with the tracing on the paper. Position settings for the foot and dynamometer used for doming strength testing were

also recorded during the initial testing session and used for all subsequent testing.

Peak force measurements were determined using a custom LabView (National Instruments, Inc., Austin, TX) program. A trained researcher visually inspected each force curve, choosing the peak of the largest plateau during the trial. Six data points around the peak were averaged to generate an average peak force for the trial. Peak forces from three trials of each test were averaged together for use in the statistical analysis.

Statistical analysis. Mixed model ANOVA (three groups three times) were run for each dependent variable to determine if groups changed differently over time (interaction effect). Main effects for group or time were not reported independently, as these were not of interest in this study. When there was a significant interaction between group and time, *post hoc* repeated-measures ANOVA were run on each group separately to determine if there were significant increases in muscle size and strength between weeks 0, 4, and 8. To determine if any increases were significantly different between groups, the changes in each variable between weeks 0 to 4, 4 to 8, and 0 to 8 were analyzed using ANOVA. Significance for all ANOVA was set at $\alpha = 0.05$. The Benjamini–Hochberg method of correcting for multiple comparisons was used with a false discovery rate of 0.10 (28).

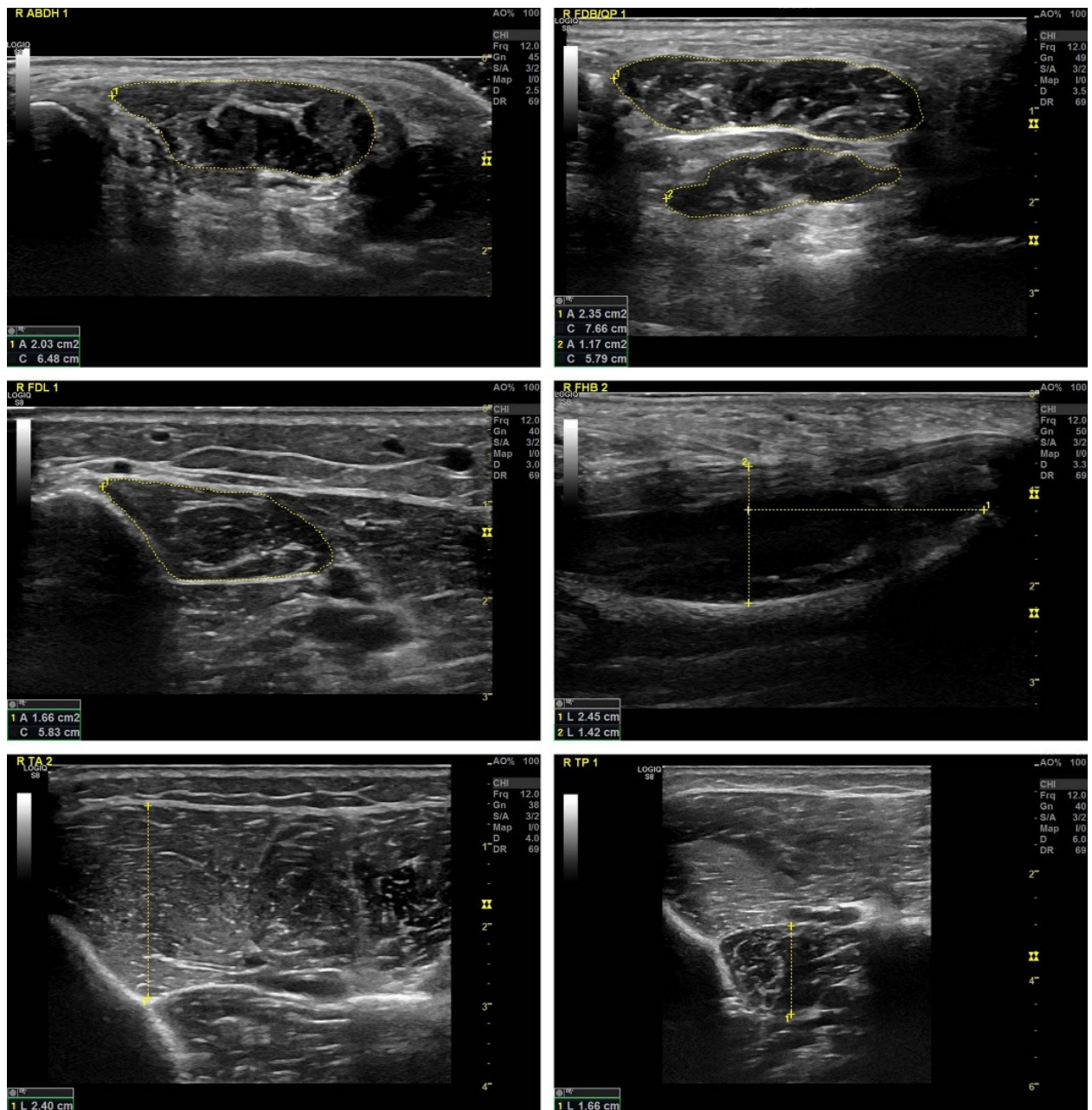


FIGURE 1—Ultrasound images of each of the seven measured muscles.

Results

All muscle size and strength data showed statistically significant interactions between group and time (all measurements except GT, LT, and FDL; $P < 0.003$; GT, $P = 0.039$; LT, $P = 0.017$; FDL, $P = 0.022$).

All muscles measured in the FS and MSW groups increased significantly in size from weeks 0 to 8 (Fig. 2; see also Appendix 1, Supplemental Digital Content 1, aggregate size and strength data, <http://links.lww.com/MSS/B376>). The average muscle size change from weeks 0 to 8 in the FS group was $11.32\% \pm 2.86\%$ of the baseline value. The MSW walking group

showed an average change of $7.05\% \pm 2.92\%$ over the same period of time. There were no changes in muscle sizes in the control group between weeks 0, 4, and 8 (average change from week 0 to 8 was $-0.08\% \pm 1.35\%$). The average percent change for each muscle is listed by group in Appendix 1 (Supplemental Digital Content 1, aggregate size and strength data, <http://links.lww.com/MSS/B376>). In the FS group, six muscles increased significantly in size at week 4, whereas three muscles increased significantly in MSW.

In comparison to the control group, all muscles changed significantly more in the FS and MSW groups from week 0 to week 4, except for the FDL (in the FS group) and the FHB (in the MSW group) (Fig. 3; see also Appendix 2, Supplemental Digital Content 2, aggregate change in size and strength data, <http://links.lww.com/MSS/B377>). The FS group experienced significantly greater size changes for the FHB (weeks 0–4, 4–8, and 0–8), QP (weeks 4–8), and FDB (weeks 4–8) than the MSW group. All other changes in muscle size were not significant between the FS and MSW groups.

The FS and MSW groups showed significant increases in strength in all three tests from week 0 to 8 (Fig. 2; see also Appendix 1, Supplemental Digital Content 1, aggregate size and strength data, <http://links.lww.com/MSS/B376>). Strength of the control group did not change at any time. Average percent changes for all strength tests were C = $4.98\% \pm 2.94\%$, FS = $58.48\% \pm 33.91\%$, MSW = $41.11\% \pm 12.55\%$.

The average percent change for each strength test is listed by group in Appendix 1 (Supplemental Digital Content 1, aggregate size and strength data, <http://links.lww.com/MSS/B376>).

Comparison of strength between groups at the beginning of the study showed that the FS group was significantly weaker than the control group during the doming test ($P = 0.032$). At week 4, both FS and MSW groups increased doming and GT flexion strength. The increases in strength in the FS and MSW groups were not significantly different than each other.

Discussion

The purpose of this study was to measure the changes in foot muscle size and strength following an exercise or MSW intervention. Our results suggest that either intervention provides sufficient stimulus to increase muscle strength significantly. While it was expected that direct exercise would result in increased muscle size and strength, it was encouraging to find that the MSW resulted in similar improvements. We theorized that if a MSW intervention was as effective for strengthening, it could be easier to implement and have a higher compliance rate than a progressive resisted exercise protocol.

Minimalist shoe walking may be effective because it may require more muscle activation to support the foot, due to the decreased cushion and support of minimalist shoes. The current study shows that this is sufficient stimulus to induce hypertrophy and strength changes within the lower leg and foot. In MSW, this stimulus is stress that is placed on the intrinsic and extrinsic foot muscles throughout the stance phase, causing the muscles to adapt and increase strength and size. In addition, increasing the load by decreasing the cushioning may initiate the release of growth factors, resulting in increased protein synthesis and muscle hypertrophy (29,30). Previous research showing that intrinsic foot muscle activity is lower in runners when running barefoot than shod presents conflicting evidence to the current study and others

showing increases in intrinsic foot muscle size after running in minimalist footwear (20–22, 31). It is possible that, in the current study, requiring the foot to go through a greater range of motion (heel to toe walking, rather than midfoot striking during running) allows the intrinsic foot muscles to activate more to control the movement of the arch.

Previous research has shown that the intrinsic foot muscles are active under a variety of loading conditions. Though there is little to no intrinsic foot muscle activity during an unshod, unweighted condition, controlled loading studies have shown that as loading of the medial longitudinal arch increases, intrinsic foot muscle activity increases (32,33). Kelly et al. (34) showed intrinsic foot muscle activity during barefoot quiet stance (body weight loading) in 10 healthy males. Other research has shown that the intrinsic musculature of the foot is active during barefoot walking, particularly during terminal stance (7,35), and that as speed increased from walking to slow running to fast running, intrinsic foot muscle (specifically the ABDH, FDB, and QP) activity also increased (7). Although barefoot walking may differ from minimalist footwear walking, the general lack of external support seems to have similar effects on the foot.

Little research has been conducted on populations that walk in minimalist footwear. One recent study showed that there are differences in ground reaction forces between walking barefoot and in minimalist footwear (36). Another compared intrinsic foot muscle size in Tarahumara men who habitually wear minimalist footwear to American men who habitually wear supportive shoes (37). The ABDH and abductor digiti minimi were larger in the Tarahumara, whereas the FDB was not significantly different in size (37).

The literature on habitually unshod populations suggests that there is increased foot muscle activity due to increased forces placed on the intrinsic muscles when weight-bearing (38). We are unaware of any studies that have reported foot muscle size in habitually barefoot subjects, though Aibast et al. (39) compared toe flexion and foot shortening (doming) muscle strength in habitually shod and habitually barefoot adolescent populations in Kenya. The habitually barefoot group was significantly stronger when performing GT flexion and doming strength tests, similar to our findings after 8 wk of foot strengthening exercise or MSW.

Although all muscles increased in size in both intervention groups in the current study, the FHB, QP, and FDB increased significantly more in the exercise group than the walking group. The specificity of some of the exercises included in the exercise protocol (e.g., the towel curl and doming) likely required more flexor muscle activity than walking. However, the greater increase in flexor muscle sizes after exercise should not detract from the benefits of the increases caused by walking, as walking still resulted in significant size and strength increases and is a more functional activity. Because most people spend a good portion of the day walking, this may be a more efficient intervention than a set of exercises that require additional time and energy to perform (though it should be noted that we had good compliance in both MSW and FS groups in the current study).

The length of our intervention (8 wk) was chosen based on previous research on strength training that show hypertrophy between 6 and 8 wk (40). Typically, we would expect to see strength gains due to neural adaptation before size gains due to hypertrophy (40). Our 8-wk intervention was sufficient to elicit both strength and size increases in both MSW and FS. We also saw some increases by 4 wk, which suggests that shorter interventions may have some

success. It was noted that those in the FS group showed increased size earlier than those in the MSW group. In addition to the previous point regarding more directed stimulation of the measured muscle via exercise, it is also possible that the starting step count of the MSW group did not provide similar muscle stress as did the exercises in the FS group until the step count was increased at weeks 3 and 5. It is also possible that greater strength improvements could be made if participants combined the exercise and MSW interventions.

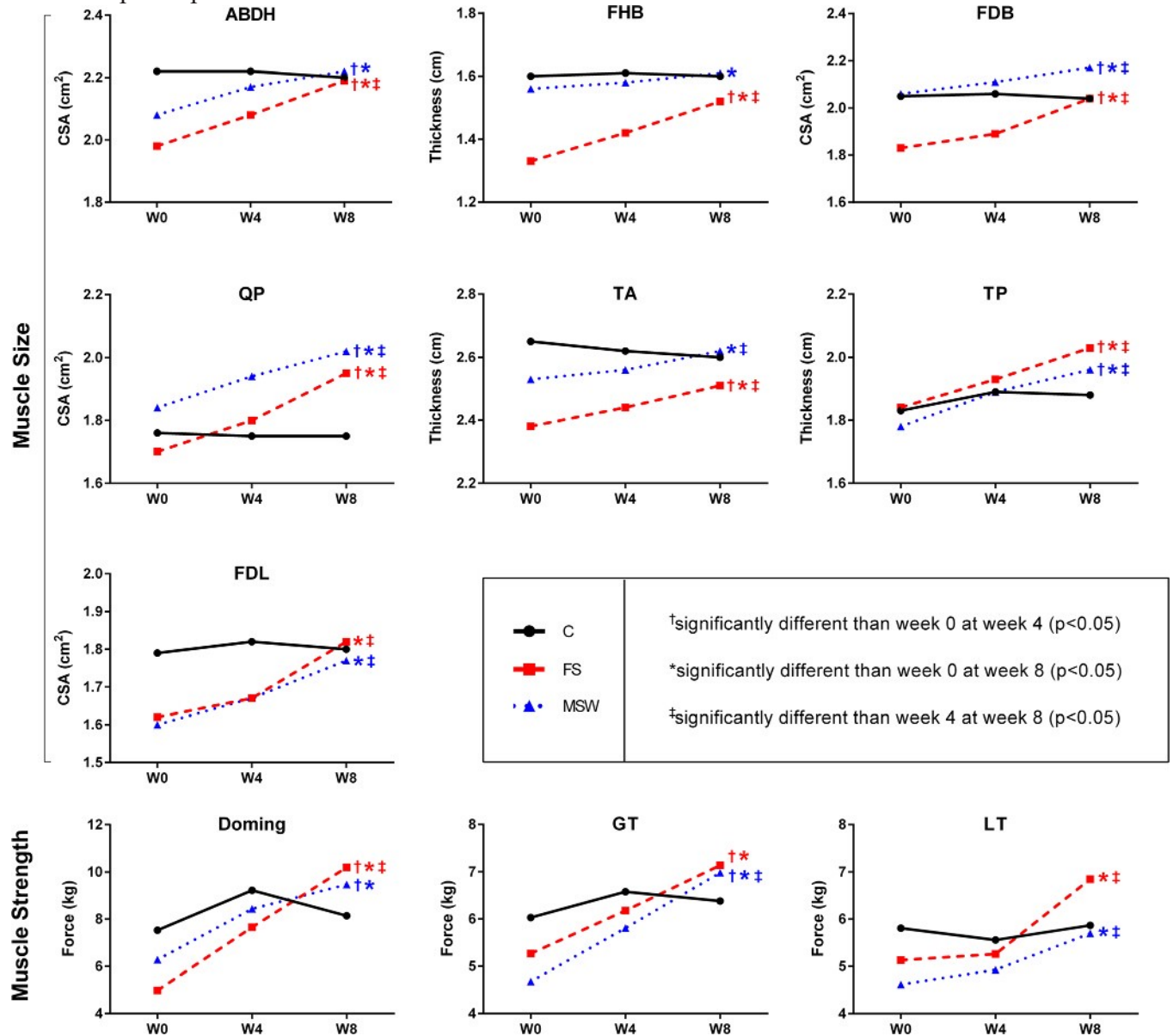


Figure 2—Muscle size and strength data for each group (C, FS) at each measurement time (W0, week 0; W4, week 4; W8, week 8). Seven muscles were measured. Three strength tests were conducted.

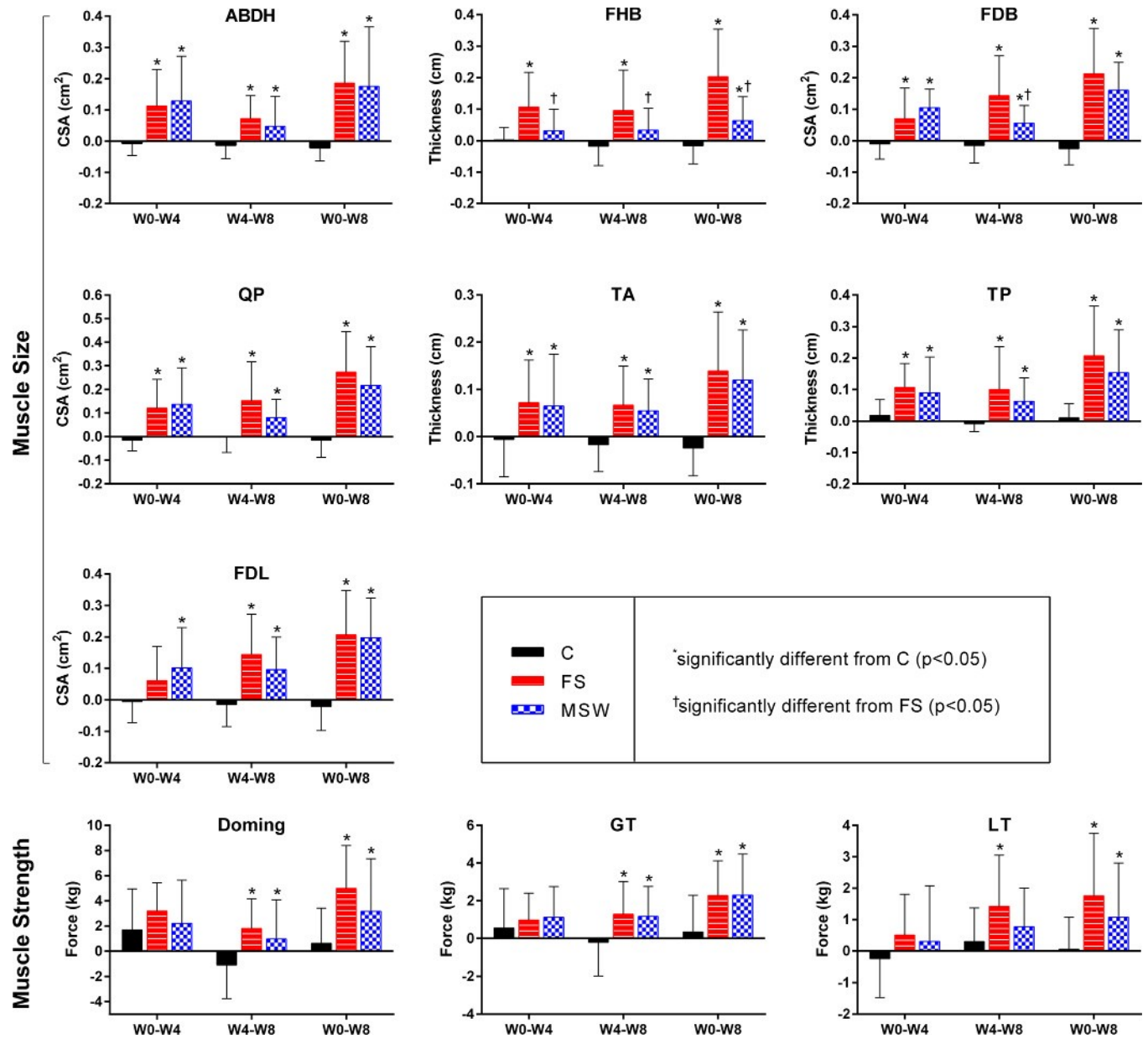


Figure 3—Muscle size and strength changes from week 0 to week 4 (W0–W4), from week 4 to week 8 (W4–W8), and week 0 to week 8 (W0–W8) for each group (C, FS). Error bars represent standard deviation. Seven muscles were measured. Three strength tests were conducted.

Limitations

There are a few limitations to this study that should be noted. First, we did not monitor the footwear subjects wore daily for activities other than running (with the obvious exception of the MSW walking group during their assigned number of minimalist footwear walking steps). Additionally, it is difficult to completely isolate intrinsic foot muscles for strength testing. Our testing methods were designed to try to minimize extrinsic activity and researchers watched subjects closely during testing to observe any unwanted movement indicative of extrinsic

activation. There were, however, some difficulties with the strength testing equipment. Repeated testing relied on similar positioning of the subject's foot during each testing session. Although we had multiple researchers involved in data collection, each subject was assigned one researcher to follow them through the study. This helped ensure greater reliability of measurements (27). Some subjects reported difficulty gripping the carabiner attached to the dynamometer for toe flexion testing. Doming was a new movement for many subjects, so it is possible that there was a learning effect. However, we taught subjects the movement when they first visited the laboratory to complete the paperwork and asked them to practice the movement for the subsequent days (no more than 3) before coming in for their baseline testing. We believe that this helped decrease any potential learning effect. Although the strength testing procedures were designed to be functional and provide information about activation, rather than just hypertrophy, they also did not target all of the muscles that were measured via ultrasound. That may also account for some differences in the timing of strength and size gains throughout the study. It also should be noted that after the 8-wk interventions, the sizes of four of the seven measured muscles (ABDH, FHB, TA, and FDL) were similar in all groups. In these muscles, the C group had larger muscle sizes than the intervention groups at week 0. It is possible that there is a ceiling effect and these muscle sizes could not change in the C group. It is more likely, however, that the lack of increase in muscle size in the C group should be attributed to the lack of participation in a strengthening intervention.

Last, as with any training study, we relied on the subjects to honestly report their participation in the interventions. Although the number of steps taken in minimalist footwear was relatively objective (though the accuracy did rely on the subjects wearing the pedometer correctly and only when wearing the minimalist footwear), compliance with the exercise intervention is harder to quantify. Subjects completed training logs which indicated that they did the exercises, but there was no indication of how well they performed them or if they just went through the motions.

Clinical Applications

Minimalist footwear use has been primarily targeted toward reducing injuries in runners. Research that focuses on runners who have transitioned to minimalist shoes shows increased muscle size in both feet and legs (20–22), suggesting that the increased stimulus triggered strengthening in the intrinsic foot muscles. However, previous research from our laboratory showed that 50% of runners who transitioned to minimalist shoes by merely gradually increasing their running mileage developed a bone stress injury over the course of the 10-wk study (23). Based on those results, it is clear that habitual traditionally shod runners need to prepare their feet for the increased stress of running without cushioning before beginning training in minimalist footwear. Either of these interventions used in the current study show potential for this use.

Although most of the research on minimalist footwear has focused on running, there are a number of clinical populations that may benefit from MSW. Previous studies have shown that 6 months of walking in minimalist footwear relieved pain and decreased knee loading in subjects with knee osteoarthritis (41, 42). Neither study reported ankle kinematics or kinetics, so the mechanism of pain relief and unloading is unclear. In addition, intrinsic and extrinsic

foot muscle strength were not measured, but based on the results of the current study, it can be inferred that muscle strength would have increased after 6 months of walking in minimalist footwear. It should be noted, however, that a more diverse population of subjects, rather than active runners, may experience different results than our subjects did.

Intrinsic foot muscle weakness has been associated with the occurrence of plantar fasciitis (3–5, 43, 44). Few studies have used a strengthening intervention in people suffering from plantar fasciitis, but those that have shown decreased pain (6, 15). If short-term pain relief can be found, subsequent strengthening of the intrinsic and extrinsic foot muscles may result in more effective rehabilitation from plantar fasciitis and decreased recurrence rates by reducing the stress transmitted through the muscles to the plantar fascia.

A variety of studies have shown benefits of foot/ankle muscle strengthening in subjects with diabetic neuropathy. Dynamic balance training and ankle flexor/extensor muscle strengthening resulted in increased gait endurance with subjects with diabetic neuropathy (16). Other study has shown that increased intrinsic foot muscle size or strength is correlated with better balance and/or fewer falls (45–47). Sartor et al. (48) also showed improved plantar pressure distribution and better foot rollover after subjects participated in an intervention including stretching, strengthening, and functional foot and ankle exercises. Finally, a recent preliminary study showed ROM and sensory perception improvements in subjects with diabetic neuropathy after a barefoot, weightbearing exercise program (17). Again, the results of the current study suggest that exercise interventions may be replaced with minimalist footwear walking, which may have greater compliance rates.

Conclusions

In conclusion, strengthening intrinsic and extrinsic foot muscles is possible through directed exercise or removing support footwear during walking. This may be beneficial to runners who suffer from a variety of foot/gait-related pathologies. Future studies are necessary to determine if strengthening foot musculature will result in decreased injury rates and/or improved function in this or other pathological populations.

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