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Original article

# The effect of minimal shoes on arch structure and intrinsic foot muscle strength

Elizabeth E. Miller [a], Katherine K. Whitcome [a,*], Daniel E. Lieberman [b], Heather L. Norton [a], Rachael E. Dyer [c]

[a] Department of Anthropology, University of Cincinnati, Cincinnati, OH 45221-0380, USA
[b] Department of Human Evolutionary Biology, Harvard University, Cambridge, MA 02138, USA
[c] Department of Biomedical, Chemical and Environmental Engineering, University of Cincinnati, Cincinnati, OH 45221-0380, USA

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**Abstract**

*Background*: This prospective study explored the effects of endurance running (ER) in minimal versus standard running shoes on the foot's superficial layer intrinsic muscles and the function of the longitudinal arch. Our hypothesis was that running in minimal shoes would cause hypertrophy in these muscles and lead to higher, stronger, stiffer arches.
*Methods*: The hypothesis was tested using a sample of 33 healthy runners randomized into two groups, a control group shod in traditional running footwear and an experimental group shod in minimal support footwear, whose feet were scanned in an MRI before and after a 12-week training regime. Running kinematics as well as arch stiffness and height were also assessed before and after the treatment period.
*Results*: Analysis of anatomical cross-sectional areas and muscle volumes indicate that the flexor digitorum brevis muscle became larger in both groups by 11% and 21%, respectively, but only the minimally shod runners had significant areal and volumetric increases of the abductor digiti minimi of 18% and 22%, respectively, and significantly increased longitudinal arch stiffness (60%).
*Conclusion*: These results suggest that endurance running in minimal support footwear with 4 mm offset or less makes greater use of the spring-like function of the longitudinal arch, thus leading to greater demands on the intrinsic muscles that support the arch, thereby strengthening the foot.


*Keywords:* Endurance running; Foot strength; Foot strike; Intrinsic foot muscles; Longitudinal arch; Minimal support footwear

## 1. Introduction

Approximately 10% of the U.S. population regularly participates in endurance running (ER).[1] Almost all of them run in highly cushioned shoes with elevated heels, stiff soles, and arch supports, designed to increase running comfort, especially on hard substrates.[2] However, throughout much of human evolution humans ran barefoot or in minimal footwear, whose earliest direct evidence is approximately 10,000 years old.[3] Minimal footwear design today differs markedly from conventional running shoes. Minimal shoes became popular in the 1970s, by featuring smaller heels, little to no cushioning, more flexible soles, and no built-in arch supports.[4] Despite perceived benefits of modern conventional running shoes, several aspects of their design likely affect the spring-like function of the longitudinal arch during stance.[5] During the first half of stance, the arch deflects inferiorly, stretching the many muscles, ligaments and other connective tissues that hold the arch together. It subsequently allows these tissues to

* Corresponding author.
*E-mail address:* katherine.whitcome@uc.edu (K.K. Whitcome)
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recoil during the second half of stance, releasing elastic energy to help raise the body's center of mass.[6–9] Conventional running shoes have several features, notably rigid arch supports, which enhance comfort but potentially restrict this motion. In addition, most shoes have stiffened soles and toe-springs that lessen how much work the intrinsic muscles have to do.[10]

Although conventional shoes are built with features which reduce the workload of the foot's intrinsic muscles, these features potentially interfere with the normal function and development of the arch. If shoes weaken the intrinsic muscles, they could increase the likelihood of a low or collapsed arch (pes planus), which not only lessens the arch's ability to act as a spring and a shock absorber but also promotes excessive pronation.[11] Over pronation is linked with a greater risk of injury due to increased rearfoot motion, tibial accommodation and other components of the lower extremity kinetic chain.[3,11,12] In addition, weak intrinsic foot muscles likely increase the load that must be borne by the plantar fascia, increasing the possibility and severity of plantar fasciitis.[12,13]

The hypothesis that standard running shoes may contribute to atrophy of the intrinsic foot muscles is conjectural, in part because of the challenges of measuring the force production of these muscles. The few studies that have addressed this issue have various limitations. Robbins and Hanna[14] reported that subjects who spent 4 months in various unspecified barefoot weight-bearing activities shortened the long axis of the medial arch increasing arch height. Robbins and Hanna,[14] however, did not assess variation in the treatment and control conditions relevant to how the arch was loaded, they did not control for activity, and they assessed the effects of being barefoot using only radiographs to quantify arch height on a self-constructed wooden board atop a spring. More recently, Brüggemann and colleagues[15] compared cross-sectional muscle area from 25 subjects who used Nike Frees to warm up (but not run) for 5 months compared with 25 controls who used traditional training shoes for the same program. This study, published as a conference abstract, found that warming up in a non-structured minimal shoe (the Nike Free; Nike, Inc., Beaverton, OR, USA), was associated with an increase in the anatomical cross-sectional area (ACSA) and strength of four plantar muscles of the metatarsophalangeal joints. This study, however, did not directly examine the strength effect of minimal shoes among habitual endurance runners, test the accuracy of the magnetic resonance imaging (MRI) measurements, or consider (self-reported or otherwise) variation in the type of warm up activities or amount of time spent in minimal footwear. Thus, the effect of running with minimal support footwear on foot strength associated with ER remains poorly understood.

Another factor to consider when assessing the effect of shoes on arch conformation is kinematic variation. Whereas most shod runners use a rearfoot strike (RFS), which leads to a large impact peak in the vertical ground reaction force, barefoot and minimally shod runners are more likely to land with a forefoot strike (FFS) or midfoot strike (MFS).[16–21] An FFS generates no discernable impact peak and also loads the arch differently than RFS. Perl et al.[9] showed that the arch in an RFS is not loaded until foot flat, and undergoes less deformation than in an FFS, which loads the arch from the moment of contact in three-point bending. However, the effect of these different loading patterns on arch conformation has not been tested.

Therefore, there are several reasons to hypothesize that minimal shoes engage the intrinsic muscles of the foot to a greater extent than conventional running shoes, since they lack built-in arch support and have lower heels and more flexible midsoles. Therefore, runners who transition to minimal footwear are predicted to increase foot strength by increasing the CSA and volume of the intrinsic plantar musculature. However, this hypothesis needs to be tested more thoroughly. This study therefore used a randomized controlled study design to test three hypotheses about the effects of running in minimal shoes on the arch and intrinsic muscles of the foot. First, we tested if runners who transitioned from standard running shoes to minimal footwear landed with more of an MFS or FFS. Second, we tested if runners who adapt to a minimalist shoe increased the ACSA and muscle volume (MV) of the three main intrinsic muscles of the longitudinal arch. These include the abductor hallucis (ABH), flexor digitorum brevis (FDB), and abductor digiti minimi (ADM), all of which run like longitudinal bowstrings from the calcaneus to the metatarsals or phalanges.[22] These most superficial intrinsic plantar muscles span much of the long axis of the foot and are easiest to measure using MRI as it distinguishes well between bone and soft tissues. Finally, we tested the hypothesis that runners who transitioned to minimal support footwear developed higher, stronger arches.

## 2. Methods

### 2.1. Subjects

Thirty-three healthy adults (17 males, 16 females) were solicited from the Cincinnati area. Inclusion criteria required an average of 30 running miles per week (48.3 km/week) in standard running shoes for no less than 12 months. Exclusion resulted from minimal shoe running, barefoot activities, or any lower limb injury within the previous year that restricted running for more than 5 consecutive days. Subjects were randomly assigned to one of two study groups (Table 1). The control group ($n = 16$) ran only in conventional footwear with plastic arch supports and a cushioned heel offset approximately 12 mm from the midsole height at forefoot to midsole height at heel. Footwear among control subjects was self-selected, and all shoes met the standard design requirement. Shoe brand and model were individually assessed according to the criteria and recorded for each participant. Subjects assigned to the experimental group ($n = 17$) transitioned from standard running footwear to minimal support footwear that lacked built-in arch support, provided reduced cushioning, and had a forefoot-heel offset of 4 mm or less. Minimal models included the New Balance® Road Minimus 10 (4 mm offset; New Balance®, Boston, MA, USA) or Merrell® Pace/Trail Glove (0 mm offset; Merrell®, Rockford, MI, USA). Subject

Table 1
General descriptive statistics of study groups (experimental and control) (mean ± SD).

| Group | Age (year) | Height (cm) | Body mass (kg) | Prior weekly mileage (km) | Study weekly mileage (km) |
|---|---|---|---|---|---|
| Experimental ($n = 17$) | 30.5 ± 4.0 | 176.4 ± 8.6 | 69.9 ± 10.2 | 46.4 ± 8.6 | 41.3 ± 13.8 |
| Control ($n = 16$) | 29.9 ± 5.5 | 177.8 ± 9.9 | 69.6 ± 8.7 | 51.2 ± 21.7 | 42.7 ± 22.8 |

and minimal shoe model were randomly paired. All participants were asked to follow one of two custom designed training programs. Those who ran only in conventional shoes maintained a weekly regimen of 30 shod miles (Appendix 1). Those transitioning to minimal shoes matched weekly mileage with the control group while gradually increasing the percentage of minimally shod miles (Appendix 2). In an attempt to prevent injuries associated with abrupt transition to minimal support footwear[4,23] our transitioning protocol eased runners into greater minimal footwear mileage across a longitudinal 12-week study. Transitional runners were encouraged to maintain vertical trunk posture, use a high cadence and avoid overstriding,[4] but they were not instructed on foot strike. All subjects were advised to report occurrence of running pain and injury. The Institutional Review Board of the University of Cincinnati approved the study, and all participants gave written consent.

### 2.2. Kinematic foot strike data collection and processing

Running kinematics were captured for each subject on a standard treadmill (Smooth Fitness 76HRPRO, King of Prussia, PA, USA) using an eight-camera Vicon MX T10 3D motion capture system (Vicon Nexus, Centennial, CO, USA) at 120 fps and a Basler Pilot pia640 monochrome high-speed digital camera (Balser AG, Ahrensburg, Germany). Video recording occurred at 200 fps with the lens set perpendicular to the long axis of the treadmill at distance of 1.0 m and 0.5 m above the lab floor. All trials were of 10-s duration following a brief period of treadmill acclimation: two quiet stance trials (recorded before and after gait trials), two walking trials at 1.25 m/s and three at 1.75 m/s, and self-determined running speeds for seven trials at half of race pace and seven at half marathon race pace. During the initial baseline session, all participants wore standard running shoes. Subsequently, the experimental group began transitioning to minimal footwear. For the concluding post-treatment session, the control group ran in standard shoes and experimental group in minimal footwear. The foot strike event was identified visually (by EEM) on synchronized high-speed digital video and 2D Vicon reconstruction run at 1/8th speed. Video based foot contact was assessed relative to the treadmill deck. Vicon 2D contact was then identified by first foot marker deceleration to zero, either the heel or metatarsal head marker. Vicon frame numbers associated with foot contact were recorded and later processed with custom MATLAB (Math Works Inc., Natick, MA, USA) scripts filtered through a 4th order zero-lag low-pass Butterworth filter with a cut-off frequency of 10 Hz.

Following Lieberman et al.,[21] we calculated the right foot angle of incidence (AOI) at foot strike as the angle between the foot segment defined by 14-mm markers overlying the left lateral malleolus and the fifth metatarsal head (LMT5), and a global horizontal through the LMT5. The running AOI was standardized to the angle obtained in quiet stance (Table 2). We identified foot strike type by AOI as an angle greater than 0° indicating forefoot contact (FFS), less than 0° heel strike (RFS), and an angle equal to 0° indicating midfoot contact (MFS)[21] (Table 2).

### 2.3. MRI data acquisition and processing

Because there is no direct method to measure force production of the ABH, FDB, and ADM, we used muscle CSA and MV to assess strength of the intrinsic muscles based on correlations between maximal force production and muscle area and volume.[24−29] In order to quantify CSA and MV, we performed same-day MRI scans matched to the kinematic session schedule. Five 1.5 T scans of the left foot were performed at each session following methods of Recht and Donley[30] (Siemens Magnatom Espree; Siemens AG, Erlangen, Germany). With the body supine and the medial malleolus centered within the scanner coil, the foot assumed plantarflexion of 10°−20° and external rotation of 10°−30°. To suppress fat tissue from appearing brighter, as it does in turbo spin echo (TSE), both the axial and sagittal tests were performed with a fat saturation scan to reduce the contribution of the fatty acids to the MR signal.[30] Coronal, sagittal, and axial scans were later viewed to identify muscle length, shape, and attachments. Axial scans only allowed reliable measurement of CSA and MV.

Each muscle was measured from the T2 TSE fat saturation axial scan along its full length. CSA was obtained by tracing muscle belly perimeters of each MRI slice using a Wacom Intuos 3 66-square inch pen tablet (www.wacom.com)[25] (Table 2). DICOM images of the muscles were then imported into ImageJ planimetric software (v1.44, http://rsb.info.nih.gov/nih-image/) where they were outlined and areal dimensions were quantified for each scan slice. We validated the MRI protocol by comparing the ImageJ acquired maximum CSAs to direct sliding caliper measurements taken on the maximum CSAs of the ABH, FDB, and ADM of a left cadaver foot obtained from an anonymous adult male. Five independent ImageJ measurements on each muscle were taken over multiple days (single observer: EEM). Mean measurement relative error was 4.3% for the ABH, 1.9% for the FDB, and 0.2% for the ADM.

The MRI acquired CSAs of all axial scan slices for each intrinsic muscle were averaged to obtain the ACSA[28] (Table 2). The MRI based CSA was further used to calculate MV (Table 2). Relationships between the muscle size variables and

Table 2
Study variables including abbreviations, definitions and source.

| Type | Name | Definition | Source |
|---|---|---|---|
| Muscle strength | Cross-sectional area (CSA) ($mm^2$) | CSA was calculated by tracing around the outline of the muscles in ImageJ using axial view magnetic resonance (MR) images. The area within the line traced was calculated by a computer-based planimetric technique (ImageJ). | Maughan et al.,[25] 1983 |
| | Anatomical cross-sectional area (ACSA) ($mm^2$) | CSAs were summed and then averaged. This was considered the ACSA. | Bamman et al.,[28] 2000 |
| | Muscle volume (MV) ($mm^3$) | MV calculated by multiplying the CSA of each slice by its linear distance (5 mm) from the previous slice (i.e., CSA1 × 5 = MV1). Then each of these products was summed (i.e., MV1 + MV2 +…+ MVn) giving the total MV for a single muscle. | Bamman et al.,[28] 2000 |
| Anthropometric | Arch height (mm) | Arch height taken at 50% of foot length with a vertical caliper measuring from the ground to the top of the dorsum. | Butler et al.,[31] 2008 |
| | Total foot length (mm) | Total foot length measured from most posterior point of the calcaneus to the distal end of the longest toe. | Butler et al.,[31] 2008 |
| | Truncated foot length (mm) | Truncated foot length (foot length minus toes) measured from the most posterior point of the calcaneus to the first metatarsophalangeal joint. | Butler et al.,[31] 2008 |
| | Arch height index (AHI) | AHI calculated as the arch height at 50% the total foot length divided by truncated foot length. | Butler et al.,[31] 2008 |
| | Relative arch deformation (RAD) | RAD obtained by dividing the difference of the unloaded arch height and arch height in single support by the unloaded arch height and multiplying that value by $10^4$ divided by body weight. | Modified from Nigg et al.,[32] 1998 |
| Kinematic | Lateral malleolus (LMA) | 3D position of the external marker over lateral malleolus of distal fibula. | – |
| | Fifth metatarsal (MT5) | 3D position of the external marker over distal metatarsal head of 5th ray. | – |
| | Angle of incidence (AOI) (°) | AOI of the foot was computed as the angle between the horizontal plane and the line formed by the fifth metatarsal head and lateral malleolus. An AOI of 0° indicates midfoot strike (MFS), >0° forefoot strike (FFS), and <0° rearfoot strike (RFS) (normalized to the AOI in standing posture). | Lieberman et al.,[21] 2010 *supplemental materials* |

measures of both body mass and foot length were examined. Differences in body mass explained only a small portion of muscle size variation in our sample as indicated by low Pearson $r^2$ values (0.12–0.23). Correlations with foot length were similarly low for the ACSA variables (0.09–0.15) but higher for the MV variables (0.16–0.26). Thus for all analyses of relative muscle size, raw ACSA and MV variates were log normalized to foot length (lnACSA/lnFL).

### 2.4. Arch height and deformation data

We defined total foot length, truncated foot length, and arch height following Butler et al.[31] (Table 2, Fig. 1). With subjects seated, we measured linear dimensions of the unloaded left foot resting on an osteometric board using sliding calipers. Measurements were repeated with subjects standing to obtain loaded foot dimensions in both single limb support and double limb support. From these measurements we derived an arch height index (AHI) and quantified relative arch deformation (RAD), which assesses stiffness[32] (Table 2). We defined AHI as the arch height at 50% the total foot length divided by truncated foot length[31,33–35] (Fig. 1). Given independent loading of the two limbs during running, we used the AHI in single stance (AHIss) for our measure of arch height. To calculate RAD we used sitting AHI (AHsit) and AHIss in the equation:

$$\frac{\text{AHsit} - \text{AHss}}{\text{AHsit}} \times \left(\frac{10^4}{\text{BM}}\right)$$

modified from Nigg et al.[32] (Table 2).

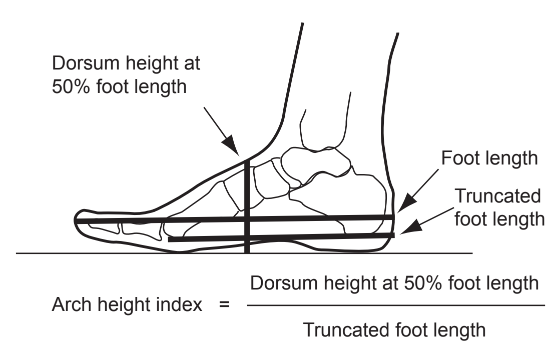


Fig. 1. The arch height index formula with visual depiction of the three measurements, total foot length, truncated foot length, and arch height.

### 2.5. Analyses

Mixed within and between subjects designs were used to test for experimental effects of minimal shoe running on the ASCA and MV of the ABH, FDB, and ADM muscles and the foot AHIss and RAD. All statistical analyses were performed in JMP (version 9.0; SAS Institute Inc., Cary, NC, USA). Normality of data was assessed with the Shapiro–Wilk *W* Test and variance homogeneity using Bartlett's Test. To identify stochastic differences between the randomly assigned groups at intake, we performed the nonparametric Wilcoxon Rank Sums Test comparing control and experimental runners. Data collected in the terminal session were examined as baseline–terminal comparisons using a nested repeated-measures multivariate analysis of variance (MANOVA) for time and time × treatment (standard shoes *vs.* minimal shoes) effects between-groups and within-subjects. Where within-subject differences were significant, we also performed within-group paired *t* tests. For all statistical tests, we used $\alpha$ 0.05 to determine significance. If no significant changes were found, the Cohen's *d* effect size (ES) was calculated[36,37] and reported and reviewed according to Cohen's effect scale[36] as small ES (0.2–0.5), medium ES ($>$ 0.5 and $\leq$0.8), and large ES ($>$ 0.8). Researchers were blind to all subjects during analyses. Of the four participants who withdrew prior to the terminal session, three control subjects variably reported insertional Achilles tendonitis, plantar fascia tear, and lower back pain. One experimental subject withdrew for non-study related reasons.

## 3. Results

### 3.1. Foot strike

All subjects ran in conventional footwear during the baseline pre-treatment trials. Foot strike pattern varied among subjects within the pooled sample ($n$ = 33) at baseline. Although forefoot and midfoot landings were infrequent, four subjects routinely ran FFS and one MFS. The remaining 28 subjects, comprising 85% of the overall sample, ran RFS. Between-group tests of the AOI showed there was no statistical difference in contact angle at baseline between the control and experimental groups ($p$ = 0.310, $d$ = 0.27, Table 3).

Table 3
Foot strike pattern reported as the angle of incidence (AOI) by group (mean ± SD).

| Group | Baseline | | Terminal | | $p^a$ |
|---|---|---|---|---|---|
| | $n$ | AOI (°) | $n$ | AOI (°) | |
| Control | 13 | −10.6 ± −8.2 | 12 | −11.1 ± −7.6 | 0.868 |
| Experimental | 15 | −8.6 ± −6.6 | 14 | −2.7 ± −7.6 | 0.035* |
| $p^b$ | | 0.310 | | 0.011 | |

*Significantly different at $\alpha < 0.05$.
[a] $p$ value between baseline and terminal.
[b] $p$ value between control and experimental.

Terminal session comparison of the AOI revealed a significant post-treatment difference between-groups ($p$ = 0.011). Upon completion of the experimental protocol, the minimally shod group had a significant 8° mean decrease in dorsiflexion at foot contact ($p$ = 0.035). Over the same study period of standard shod running, the contact AOI comparison of pre- and post-treatment within the control group was not significant ($p$ = 0.868, $d$ = 0.06). In other words, from baseline to terminal testing, distribution of control group foot strike pattern did not change. However, within the experimental group there was a shift from runners using predominately RFS at baseline to a more MFS or FFS at terminal session.

### 3.2. ACSA and MV

Baseline tests of the relative ACSA and relative MV of the ADM, ABH, and FDB muscles showed no significant pre-treatment difference between the control and experimental groups (Figs. 2A and 3A). Terminal testing revealed significant differences between the relative ACSA and relative MV of the ADM and ABH muscles of the two study groups (Figs. 2B and 3B). With 12 weeks of standard shod running, the control group significantly increased only MV of the FDB ($p$ = 0.03, Table 4, Fig. 4). Following the same 12-week period, the experimental group having transitioned to minimal shod running increased not only MV of the FDB ($p$ = 0.03, Table 4, Fig. 5) but also MV and ACSA of the ADM ($p$ = 0.009 and $p$ = 0.007, respectively, Table 4, Fig. 5). Neither group significantly increased MV or ACSA of the ABH muscle.

### 3.3. AHI and RAD

Prior to treatment, conformation of the longitudinal arch did not differ between the randomly assigned groups (Table 5). The AHIss index of mean arch height in single limb support was equivalent at 0.36 in the two groups. Similarly, group comparison of the mean RAD, our measure of stiffness, showed no initial difference between the control and experimental groups ($p$ = 0.33, $d$ = 0.33).

Neither group experienced a significant change in AHIss over the 12-week study period (Table 5). Similarly, post-treatment test of RAD showed no significant change in arch stiffness within either group ($p$ = 0.21, $d$ = 0.37). However, we identified an outlier among experimental runners at 3.5 SD from the group mean. An *ad hoc* test after outlier deletion yielded a significant effect of time by group ($p$ = 0.04). A follow-up paired *t* test of experimental runners showed significant change in post-treatment RAD ($p$ = 0.013) suggesting a stiffening of the arch with minimally shod running (Table 5).

## 4. Discussion

The results of this 12-week longitudinal study suggest that endurance running in minimal support footwear

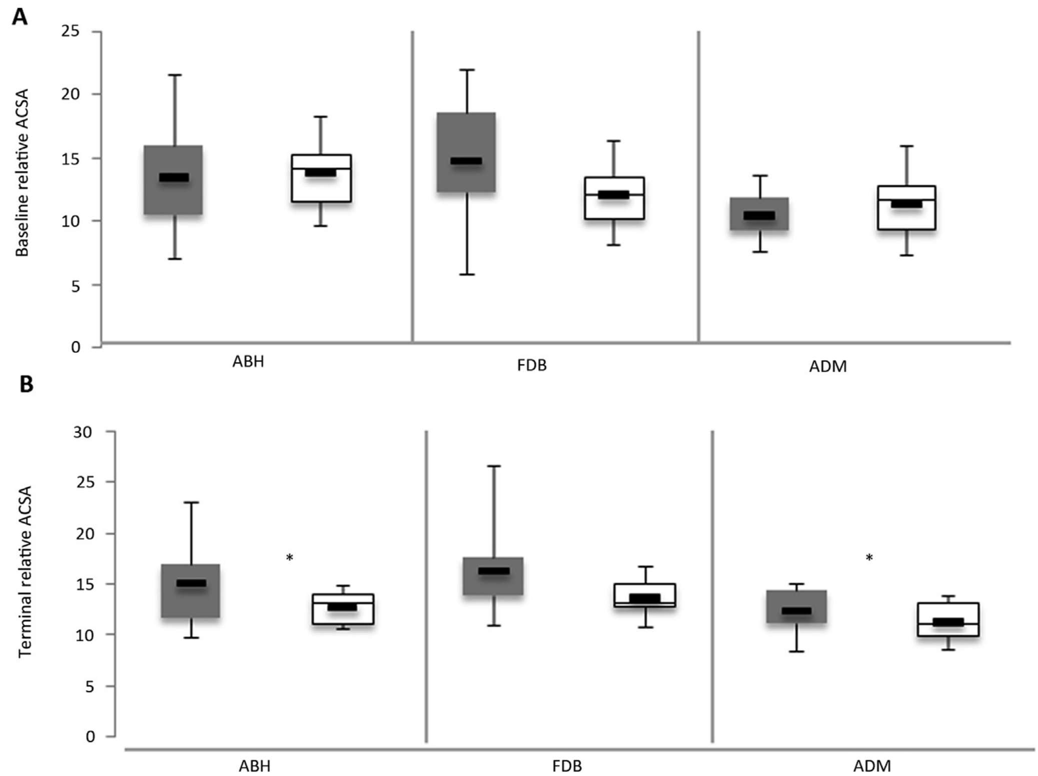


Fig. 2. Between-group tests of relative ACSA (lnACSA/lnFL) of the ABH, FDB, and ADM. Experimental group gray and control group white. Heavy black line indicates group mean. (A) Baseline session tests showed no significant group difference in relative ACSA (ABH: $p = 0.6647$, FDB: $p = 0.0579$, ADM: $p = 0.2206$). (B) Terminal session tests indicated significant group differences over time for the ABH ($p = 0.0016$) and ADM ($p = 0.0001$) and no significant difference for FDB ($p = 0.9881$). ACSA = anatomical cross-sectional area; ABH = abductor hallucis; FDB = flexor digitorum brevis; ADM = abductor digiti minimi. * indicates significant result.

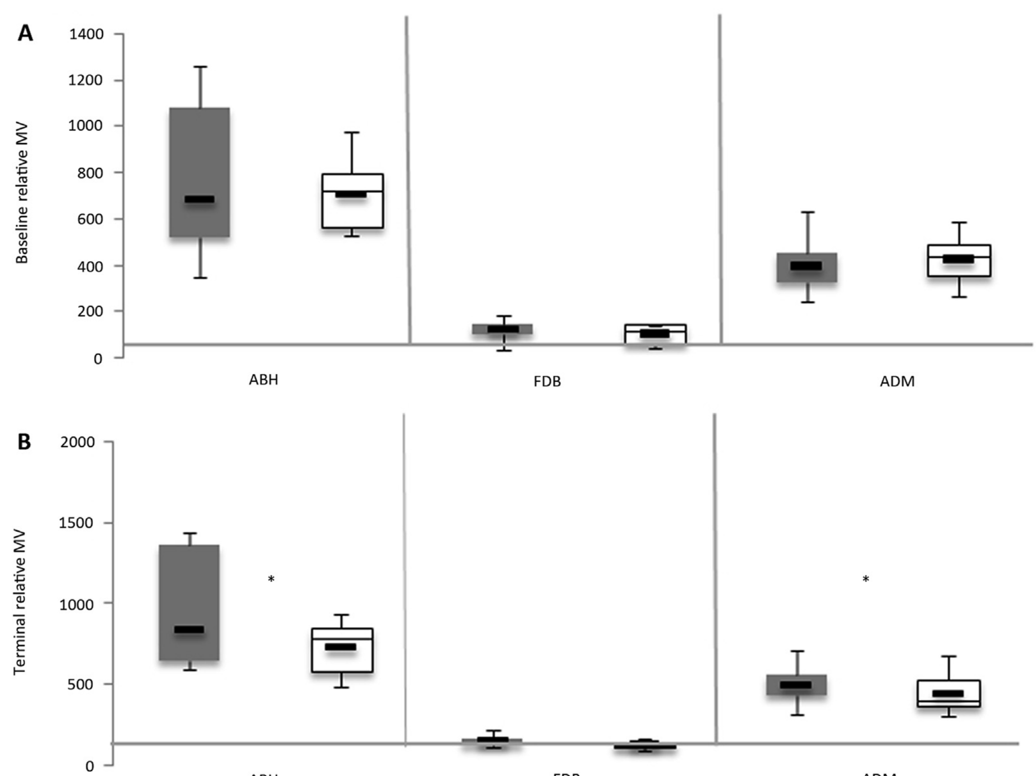


Fig. 3. Between-group tests of relative MV (lnMV/lnFL) of the ABH, FDB, and ADM. Experimental group gray and control group white. Heavy black line indicates group mean. (A) Baseline session tests showed no significant difference in relative MV (ABH: $p = 0.5847$, FDB: $p = 0.3$, ADM: $p = 0.2067$). (B) Terminal session tests indicated significant group differences in the ABH ($p = 0.0011$) and ADM ($p = 0.0256$) and no significant difference in FDB ($p = 0.5542$). MV = muscle volume; ABH = abductor hallucis; FDB = flexor digitorum brevis; ADM = abductor digiti minimi. * indicates significant result.

Table 4
Anatomical cross-sectional area (ACSA) and muscle volume (MV) of abductor hallucis (ABH), flexor digitorum brevis (FDB), and abductor digiti minimi (ADM) relative to foot length (mean ± SD).

| Group | Status | *n* | ACSA | | | MV | | |
|---|---|---|---|---|---|---|---|---|
| | | | ABH | FDB | ADM | ABH | FDB | ADM |
| Control | Baseline | 14 | 13.9 ± 0.6 | 12.1 ± 0.6 | 11.4 ± 0.6 | 711.3 ± 39.3 | 111.1 ± 6.4 | 429.1 ± 26.2 |
| | Terminal | 13 | 12.8 ± 0.6 | 13.7 ± 0.7 | 11.3 ± 0.7 | 729.3 ± 42.5 | 133.8 ± 6.9 | 441.3 ± 31.0 |
| | *p* value | | 0.20 | 0.08 | 0.90 | 0.76 | 0.03* | 0.77 |
| Experimental | Baseline | 17 | 13.5 ± 1.0 | 14.9 ± 1.0 | 10.5 ± 0.5 | 688.5 ± 61.0 | 125.1 ± 8.2 | 398.3 ± 24.6 |
| | Terminal | 16 | 15.1 ± 1.0 | 16.4 ± 1.1 | 12.4 ± 0.5 | 838.4 ± 62.8 | 152.3 ± 8.5 | 496.8 ± 25.3 |
| | *p* value | | 0.27 | 0.30 | 0.007* | 0.10 | 0.03* | 0.009* |

*Significantly different at $\alpha < 0.05$.
Repeated-measures MANOVA within-groups after 12-week protocol comparing baseline and terminal sessions.

stimulates changes in arch function and the intrinsic foot muscles of runners who previously used conventional running shoes. The experimental runners who transitioned from conventional running shoes to minimal footwear experienced multiple changes in their landing kinematics, foot musculature and arch conformation as hypothesized. No such changes were observed in the control group with the exception of an increase in flexor digitorum brevis volume. Volume appears to be a more sensitive and robust measure than CSA as the majority of significant findings were in the volume of the muscles over time. Although foot strength was not directly measured, the results of this prospective experimental study suggest that runners who transition to minimal footwear can develop a significant increase in foot strength.

At the start of the study, 85% of our subjects were RFS, a proportion well within the range of previous reports[3,4,21] and one that suggests an RFS is typical of conventional shod running at endurance speeds. As predicted, runners who adapted to a minimalist shoe over the 12-week study period shifted from a predominantly rearfoot strike pattern to more MFS or FFS landings. We found a significant decrease in dorsiflexion angle at foot contact among experimental runners in minimalist shoes and not among control runners in standard footwear. The control group remained unchanged with runners landing mainly with an RFS. Our findings agree with several other studies that have shown runners who transition from standard to minimalist or barefoot running change from RFS to more MFS/FFS,[16,17,38] just as most habitual barefoot runners often land more MFS/FFS.[18,20,21]

This change in foot strike pattern may lead to greater muscle recruitment and therefore increased work performed by muscles of the foot.[38] Runners within the experimental group who transitioned to a more MFS/FFS increased the ACSA and MV of the ADM muscle. The increase was similar for the MFS and the FFS transitions. However, ACSA and MV of the abductor muscles remained unchanged in runners who consistently used RFS. During the first half of stance the longitudinal arch deforms inferiorly in MFS and FFS,[6–9] and the intrinsic muscles spanning the arch stretch similarly to mechanical springs under tension. These muscles subsequently contract, stiffening the longitudinal arch as load shifts from the midfoot onto the ball of the foot, pulling the calcaneus and metatarsals closer. This windlass sequence does not characterize RFS because the arch stretches later in stance only during flatfoot[21] when arch stiffening and muscle stabilization are less likely.

The intrinsic ADM, ABH, and FDB muscles provide structural integrity to the medial longitudinal arch by their origins on the medial calcaneal tubercle and insertions distal to the metatarsal-phalangeal joints (MPJ).[39] As the runner's center of mass shifts to the forefoot the heel rises and the toes dorsiflex. The ground reaction force in response to MPJ rotation generates a dorsiflexion moment ranging in magnitude from 20 to 40 Nm.[40] Activation of the long and short toe flexors (ADM, ABH, and FDB) counteract the external MPJ dorsiflexion moments.[40] Although this heel rise−MPJ dorsiflexion event occurs regardless of foot strike pattern, those runners whose initial foot contact is either MFS or FFS clearly position the MPJ in greater dorsiflexion at foot contact than otherwise occurs in RFS.[9] Such repetitive contact events in which the impact force occurs during high MPJ dorsiflexion may lead to increase in both MV and CSA as the short flexors act to mitigate the high MPJ dorsiflexion moment associated with MFS and FFS contact.

We predicted that the runners transitioning from conventional running shoes to minimalist footwear would increase the MV and ASCA of the intrinsic ABH, FDB, and ADM muscles. Notably, the experimental group significantly increased both the MV and ACSAs of the ADM muscle ($p = 0.009$ and $p = 0.007$, respectively). This muscle, attaching proximally at the calcaneus and distally to the lateral base of the lateral proximal phalanx, flexes only the fifth digit and supports the longitudinal arch.[39] Evident in its volumetric and areal increase, greater force production in the ADM suggests increased recruitment of it and the longitudinal arch among minimal shoe runners. Just as barefoot running has been shown to increase work of the leg compartment triceps surae in association with increased plantarflexion moments,[9,38] our results for minimally shod running show increase in work of the foot compartment muscles in association with plantarflexion at foot strike. Importantly, volumetric and areal increases of the ADM in minimally shod runners only suggest that the mean 8° decrease in dorsiflexion (i.e., increase in plantarflexion) at foot strike affects the work of

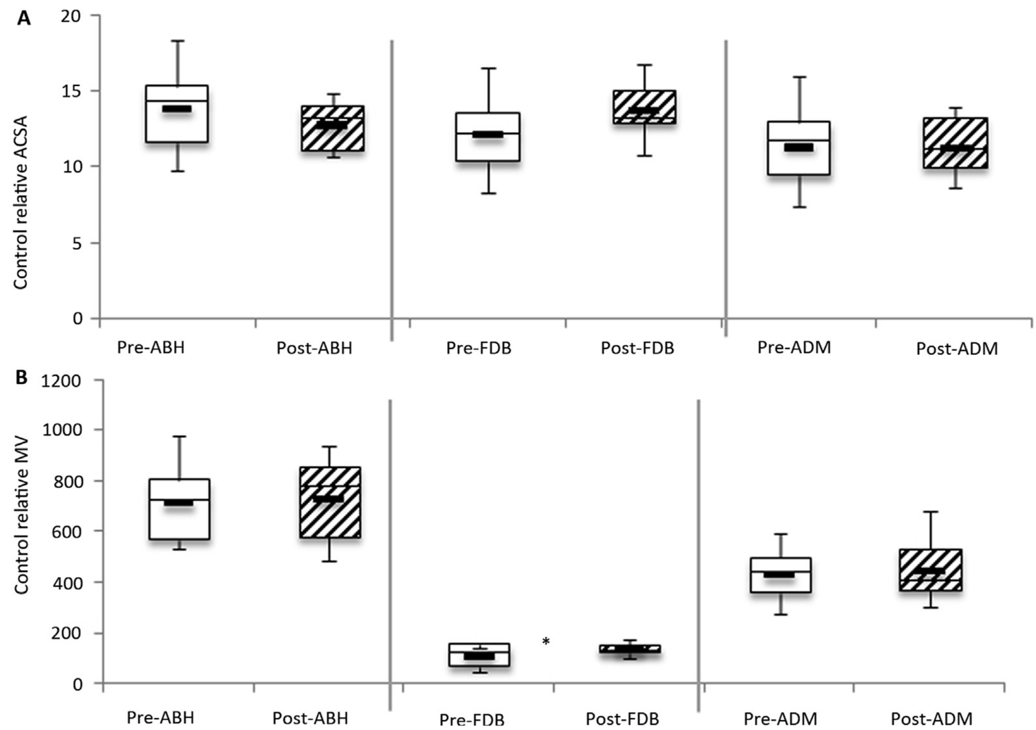


Fig. 4. Within-group tests of relative ACSA and relative MV between baseline and terminal session for the ABH, FDB, and ADM in control group. Baseline/pre-treatment session (white) and terminal/post-treatment session (striped). Heavy black line indicates group mean. (A) No significant difference in relative ACSA for all three muscles (ABH: $p = 0.2$, FDB: $p = 0.08$, ADM: $p = 0.9$). (B) Significant difference in relative MV of the FDB ($p = 0.03$). No significant difference in the ABH ($p = 0.76$) and the ADM ($p = 0.77$). ACSA = anatomical cross-sectional area; MV = muscle volume; ABH = abductor hallucis; FDB = flexor digitorum brevis; ADM = abductor digiti minimi. * indicates significant result.

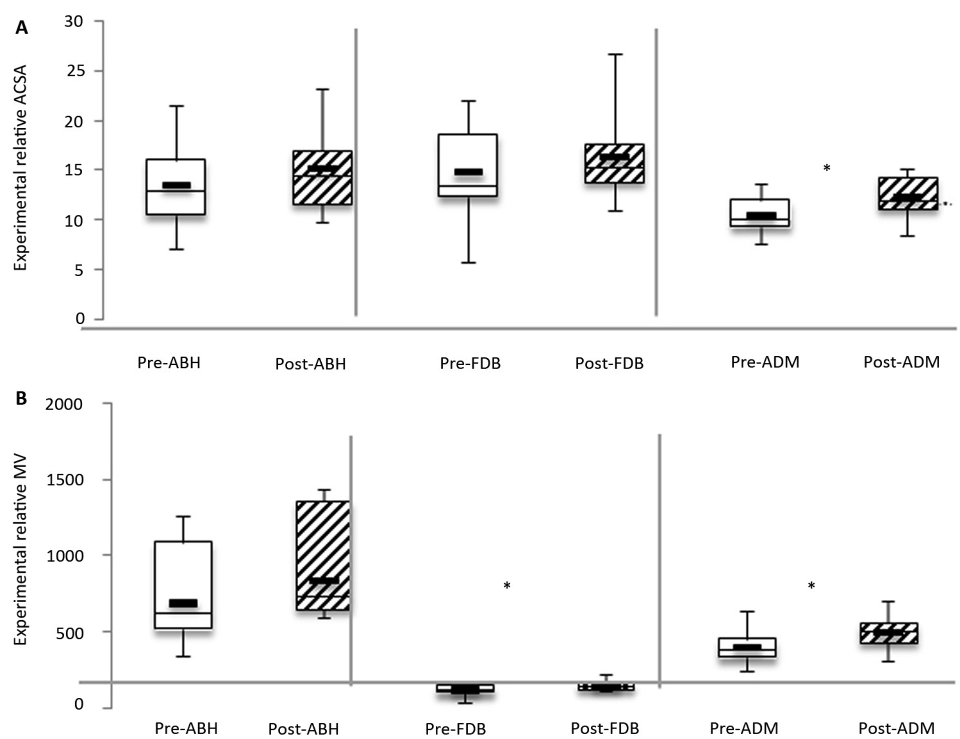


Fig. 5. Within-group tests of relative ACSA and relative MV between baseline and terminal session for the ABH, FDB, and ADM in experimental group. Baseline/pre-treatment session (white) and terminal/post-treatment session (striped). Heavy black line indicates group mean. (A) Significant difference in relative ACSA of the ADM ($p = 0.007$). No significant difference the ABH ($p = 0.27$) and FDB ($p = 0.3$). (B) Significant difference in the relative MV of the ADM ($p = 0.007$) and the FDB ($p = 0.03$) over time. No significant difference in the ABH ($p = 0.1$). ACSA = anatomical cross-sectional area; ABH = abductor hallucis; FDB = flexor digitorum brevis; ADM = abductor digiti minimi; MV = muscle volume. * indicates significant result.

Table 5
Mean arch height index in single support (AHIss) and relative arch deformation (RAD) (mean ± SD).

| Group | Status | $n$ | AHIss | RAD |
|---|---|---|---|---|
| Control | Baseline | 16 | 0.36 ± 0.03 | 5.83 ± 6.96 |
| | Terminal | 12 | 0.35 ± 0.03 | 5.98 ± 6.04 |
| | $p$ value | | 0.250 | 0.953 |
| Experimental | Baseline | 17 | 0.36 ± 0.03 | 8.77 ± 10.33 |
| | Terminal | 16 | 0.37 ± 0.03 | 3.53 ± 7.26 |
| | $p$ value | | 0.190 | 0.104 |
| | Significance with outlier omitted* | | – | 0.013* |

*Significantly different at $\alpha < 0.05$.

the ADM muscle more so than the other intrinsic muscles we examined. Of the three intrinsic muscles studied, only the ADM lies entirely within the midfoot region. Thus, routine MFS may recruit the ADM more heavily than either the FDB or the ABH and explain why it significantly increased in both volume and CSA.

Although the FDB muscle increased in relative size (MV), unlike the ADM it did so in both running groups. This suggests that sustained running, whether in standard or minimal footwear recruits the centrally positioned muscle underlying superficial plantar facsia. We suspect that endurance running, regardless of preferred foot strike pattern, heavily recruits the midline FDB. Furthermore, it appears that running without heel-cushioned and stiff midsole shoes, as in minimal footwear running, increases the work of the central FDB as well as the lateral ADM. Because minimal shoes are constructed with a low heel and have no built-in arch support, they may recruit the ADM differently than standard running shoes. Previous work has shown the occurrence of a second peak in center of pressure (COP) following initial foot contact pronation.[41] This second trajectory peak occurs more laterally in barefoot runners than in standard shod runners.[41,42] Lateral deflection and laterally oriented velocity peak of COP in the absence of built-in arch support, whether barefoot or in minimal shoe, may lead to greater demand on the ADM.

Foot muscles appear to respond quickly to increased mechanical stimuli. In a recent study of resistance training, Goldman and colleagues[40] found that an effort of 90% maximum voluntary isometric contraction repeated over 7 weeks increased intrinsic toe flexor strength 40%. Over the course of our 12-week study, running in conventional and minimal footwear led to an increase in FDB size and minimal shoe running only led to additional increase in ADM size. We interpret size change measured as increase in muscle CSA and volume to indicate greater muscle strength.[24] Increased muscle strength was likely induced by recruitment of the intrinsic group for arch stabilization during toe-off.[6,22,43,44] Whereas arch stabilization in standard footwear is largely provided by the extrinsic arch support of rigid shoe design, stability in minimal footwear is contingent only on intrinsic factors of foot conformation, including the tensile and contractile properties of muscle. Furthermore, although both groups saw an increase in MV of the FDB, in maintaining RFS throughout the longitudinal study, the control group showed no change in both abductor size and arch stiffness. In contrast, the minimal footwear group additionally increased ADM abductor size and increased arch stiffness.

We found the most robust difference between conventional shod and minimally shod groups in the variable of longitudinal arch stiffness (RAD), which increased approximately 60% in the minimally shod runners but underwent no change in the control group. Our randomly assigned groups entered the study with no significant difference in RAD and AHI in single limb support (AHIss). The pre-treatment AHIss of 0.36 for both groups was consistent with values previously reported for the habitually shod (conventional running shoe).[31,35] Most conventional running shoes place a relatively stiff support below the longitudinal arch. This support combined with a relatively stiff midsole likely reduce the extent of stretch in soft tissues during loading, and effectively replace or inhibit the natural spring mechanism of the arch.[6,9] It is reasonable to infer that these soft tissues are able to function more naturally as a spring in a minimal shoe. The abductors, which flex the hallucal and fifth digit metatarsal-phalangeal joints, also enhance the windlass mechanism of the plantar aponeurosis.[45] Thus, volumetric increase of the ADM in the minimally shod runners suggests not only greater stiffness in the minimally shod foot but also greater capacity for force production when the arch deforms and recoils. Further, MFS/FFS may heavily recruit the ADM more than the highly dorsiflexed RFS as this abductor stabilizes the longitudinal arch during initial foot strike and is held in tension until toe-off.

The results of this study suggest the need for several additional experiments. Future research on the effects of barefoot and minimal shoe running on foot strength would benefit from a larger sample size and a longer treatment period. Although the ADM and FDB responded quickly in this study and others,[40,45] a longer treatment period might be hypothesized to yield arch height differences between treatment groups. Another area for future study would be to improve the ability to delineate deep intrinsic muscles in MRI scans. We examined only superficial plantar musculature of the foot, omitting the quadratus plantae muscle that lies deep within the second layer. Finer differentiation of the interdigitating fibers of the quadratus plantae muscle would capture more of the intrinsic musculature's response to different running conditions.

Our study design aimed to vary only footwear among control and experimental subjects in order to assess effects of minimal footwear on arch structure and intrinsic foot muscle strength. However, our protocol for the experimental runners included a brief discussion on safe practice (posture and cadence) in minimal shoe running in order to prevent injury. Subjects were not instructed on which foot strike pattern to use. Nonetheless, these instructions may have led to other changes in form in the experimental group.

A potential weakness of this study was the variation of footwear worn by the both groups. The shoes worn by control subjects varied widely by model and make, but met all construction criteria. Although the experimental group used just two models of minimal footwear, which also met *a priori* criteria, the drop offset of minimal shoe models differed by 4 mm. The Merrell Pace/Trail Glove with its 0 mm differential is a more minimal shoe than the New Balance Minimus. *Post hoc* tests of experimental runners accounting for the two minimal shoe models showed a significant difference in the RAD ($p = 0.0009$), with a stiffer arch among the New Balance model runners. Thus, it is likely that the New Balance shoe required the intrinsic muscles to do more work. Nonetheless, both minimal shoes were shown to recruit the plantar intrinsic musculature of the foot more than highly cushioned standard running shoes. However, *in vivo* electromyography analyses are necessary to test this hypothesis.

To conclude, these findings support earlier studies, which suggested that running barefoot or in minimal shoes increases the overall area and volume of the plantar intrinsic musculature, makes greater use of the spring-like function of the longitudinal arch and its associated muscles, and promotes stiffer arches.[9,15,16] These results suggest that runners can adapt successfully to using minimal shoes without increased risk of injury if they do so gradually and carefully, but future studies with larger samples sizes are clearly necessary to test this hypothesis more carefully.

## Acknowledgment

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## Appendix 1.

### *Control group training plan*

Included in this packet are your training programs for the next 3 months and a key explaining the various workouts. Please make sure to read over it carefully to ensure you understand it correctly. If you have any questions do not hesitate to contact the Principal Investigator for the study, Liz Miller.

### *Key*

VE (very easy) = not faster than 70% of current 5000 pace/mile. For instance, if you can run a 5000 at 6:00/mile, VE pace would be no faster than 8:30/mile. Calculated as 6 divided by 0.70. This is near effortless pace. AC (aerobic conditioning) = 75%−82% of current 5000 pace/mile. A medium effort run.

| Week No. | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| **Month 1 − Standard running shoes** | | | | | | | |
| Week 1 | Off day | 4 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 3 miles VE | 8 miles VE-AC |
| Week 2 | Off day | 5 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 3 miles VE | 9 miles VE-AC |
| Week 3 | Off day | 6 miles VE-AC | 6 miles VE-AC | Off day | 5 miles VE-AC | 3 miles VE | 10 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | 5 miles VE-AC | Off day | 5 miles VE-AC | Off day | 4 miles VE-AC | 6 miles VE-AC |
| **Month 2 − Standard shoe training** | | | | | | | |
| Week 1 | Off day | 6 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 2 | Off day | 6 miles VE-AC | 5 miles VE-AC | Off day | 5 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 3 | Off day | 6 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | 5 miles VE-AC | Off day | 5 miles VE-AC | Off day | 4 miles VE-AC | 6 miles VE-AC |
| **Month 3 − Standard shoe training** | | | | | | | |
| Week 1 | Off day | 6 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 2 | Off day | 6 miles VE-AC | 5 miles VE-AC | Off day | 6 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 3 | Off day | 6 miles VE-AC | 6 miles VE-AC | Off day | 6 miles VE-AC | 4 miles VE | 10 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | 5 miles VE-AC | 4 miles VE | Off day | 5 miles VE-AC | Off day | 6 miles VE-AC |

## Appendix 2.

*Transition group training plan*

Included in this packet are your training programs for the next 3 months and a key explaining the various workouts. Please make sure to read over it carefully to ensure you understand it correctly. If you have any questions do not hesitate to contact the Principal Investigator for this study, Liz Miller. You will be running in your standard running shoes while transitioning into the minimalist shoes. Please make sure you note which workouts are to be done in which shoes.

*Key*

VE (very easy) = not faster than 70% of current 5000 pace/mile. For instance, if you can run 5000 at 6:00/mile, VE pace would be no faster than 8:30/mile. Calculated as 6 divided by 0.70. This is near effortless pace. AC (aerobic conditioning) = 75%−82% of current 5000 pace/mile. A medium effort run.

IMS = in minimalist shoes; ISS = in standard shoes.

| Week No. | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| **Month 1 − Minimal shoe training** | | | | | | | |
| Week 1 | Off day | **ISS**: 5 miles VE-AC | **ISS**: 1 mile VE **IMS**: 1 mile, alternating 100 m VE jog/100 m walk | **ISS**: 5 miles VE-AC | **ISS**: 5 miles VE-AC | **ISS**: 3 miles VE **IMS**: 1 mile, alternating 100 m VE jog/100 m walk | **ISS**: 8 miles VE-AC |
| Week 2 | Off day | **ISS**: 6 miles VE-AC down | **ISS**: 1.5 miles VE **IMS**: 1.5 miles, alternating 100 m VE jog/100 m walk | Off day | **ISS**: 7 miles VE-AC | **ISS**: 1.5 miles VE **IMS**: 1.5 miles, alternating 100 m VE jog/100 m walk | **ISS**: 9 miles VE-AC |
| Week 3 | Off day | **ISS**: 6 miles VE-AC | **ISS**: 5 miles VE **IMS**: 1 mile VE | Off day | **ISS**: 6 miles VE | **ISS**: 2 miles VE **IMS**: 2 miles, alternating 100 m VE jog/100 m walk | **ISS**: 10 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | **ISS**: 1 mile VE, 3 miles VE-AC **IMS**: 1 mile VE | Off day | **ISS**: 1 mile VE, 2 miles VE-AC **IMS**: 1.5 miles VE | Off day | **ISS**: 4 miles VE-AC | **ISS**: 4.5 miles VE **IMS**: 4.5 miles VE |
| **Month 2 − Minimal shoe training** | | | | | | | |
| Week 1 | Off day | **ISS**: 6 miles VE-AC | **ISS**: 4 miles VE **IMS**: 2 miles VE-AC | Off day | **ISS**: 2 miles VE-AC **IMS**: 2 miles VE-AC | **ISS**: 4 miles VE | **IMS**: 2 miles VE **ISS**: 8 miles VE-AC |
| Week 2 | Off day | **ISS**: 5 miles VE-AC | **ISS**: 2.5 miles VE **IMS**: 2.5 miles VE | Off day | **ISS**: 4 miles VE-AC **IMS**: 2 miles VE | **ISS**: 4 miles VE | **IMS**: 2.5 miles VE **ISS**: 7.5 miles VE-AC |
| Week 3 | Off day | **ISS**: 6 miles VE-AC | **ISS**: 3 miles VE-AC **IMS**: 3 miles VE-AC | Off day | **ISS**: 3.5 miles VE-AC **IMS**: 2.5 miles VE-AC | **ISS**: 3 miles VE | **IMS**: 3 miles VE **ISS**: 7 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | **ISS**: 4 miles VE-AC | **ISS**: 2 miles VE-AC **IMS**: 3 miles VE-AC | Off day | **ISS**: 3 miles VE-AC **IMS**: 2 miles VE-AC | Off day | **ISS**: 2.5 miles VE **IMS**: 3.5 miles VE-AC |
| **Month 3 − Minimal shoe training** | | | | | | | |
| Week 1 | Off day | **ISS**: 6 miles VE-AC | **ISS**: 2.5 miles VE-AC **IMS**: 3.5 miles VE-AC | Off day | **ISS**: 3.5 miles VE-AC (relaxed) **IMS**: 2.5 miles VE-AC | **ISS**: 3 miles VE | **IMS**: 4 miles VE **ISS**: 6 miles VE-AC |
| Week 2 | Off day | **ISS**: 3 miles VE-AC **IMS**: 3 miles VE-AC | **ISS**: 4 miles VE-AC **IMS**: 1 mile VE-AC | Off day | **ISS**: 3 miles VE-AC **IMS**: 3 miles VE-AC | **ISS**: 3 miles VE | **IMS**: 4.5 miles VE-AC **ISS**: 5.5 miles VE-AC |
| Week 3 | Off day | **ISS**: 3 miles VE-AC **IMS**: 3 miles VE-AC | **ISS**: 3 miles VE-AC **IMS**: 2 miles VE-AC | Off day | **ISS**: 2.5 miles VE-AC **IMS**: 3.5 miles VE-AC | **ISS**: 3 miles VE | **IMS**: 4.5 miles VE-AC **ISS**: 5.5 miles VE-AC |
| Week 4 (lower volume recovery week) | Off day | **ISS**: 4 miles VE-AC | **ISS**: 1.5 miles VE-AC **IMS**: 3.5 miles VE-AC | Off day | **ISS**: 3 miles VE **IMS**: 2 miles VE | Off day | **IMS**: 6 miles VE-AC |

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