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Original article

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

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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

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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