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Original research

The morphology of foot soft tissues is associated with running shoe type in healthy recreational runners

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Objectives: To determine the differences in the morphology of foot soft tissues between runners using different types of running shoes.
Design: Cross-sectional study.
Methods: Thirty-eight recreational runners were divided into four groups based on running shoe type, namely, neutral shoes, motion control shoes, minimalistic shoes and neutral shoes with custom-made insoles. An arch height index and a relative arch deformation index were calculated for each participant. An ultrasound device was used to measure the cross-sectional area and/or the thickness of selected intrinsic foot muscles (abductor hallucis, flexor hallucis brevis and flexor digitorum brevis) and extrinsic foot muscles (flexor digitorum longus, tibialis anterior and the peroneus muscles), and the thickness of the plantar fascia, Achilles tendon and heel pad.
Results: Recreational runners using minimalistic shoes demonstrated stiffer foot arches than those using neutral shoes. Among the selected foot muscles, only abductor hallucis showed a significant morphological difference between shoe groups. Runners using minimalistic shoes had the thickest abductor hallucis. The minimalistic shoe runners also showed a thinner proximal plantar fascia and a thicker Achilles tendon than other runners. Insole runners had a thinner heel pad than neutral shoe runners.
Conclusions: This study suggests that the morphology of foot soft tissues is associated with running shoe type in recreational runners. A sudden change in running shoe type without adjusting training volume should be undertaken with caution, since it may take time for foot soft tissues to adapt to a new shoe condition.

1. Introduction

Running is a very popular form of physical activity around the world. It has been suggested that running improves overall health, reduces the risk of respiratory and cardiovascular diseases and increases longevity.[1,2] Despite the obvious health benefits of running, the incidence of overuse running injuries ranges from 19% to 79%.[3] The aetiology of overuse running injuries is multifactorial. High impact forces and abnormal joint motion of the lower limb are widely believed to increase the injury risk.[4,5] Therefore, running shoe properties which aim to reduce impact forces and control abnormal joint motions have been developed.

Based on shoe properties, running shoes can generally be categorized as neutral shoes, motion control shoes and minimalistic shoes. Neutral shoes, which are standard shoes with cushioning properties (an elevated heel, a midsole, etc.), have been shown to reduce impact peak and loading rate during running.[6] Motion control properties, e.g. dual midsole material, have been developed to control excessive joint motions, mainly excessive foot pronation. As an alternative to motion control shoes, using custom-made insoles in neutral shoes also provides external control of excessive foot motions during locomotion. Studies have shown that both motion control shoes and custom-made insoles can reduce excessive rearfoot eversion during locomotion.[7–9] Neutral and motion control shoes are considered as conventional running shoes, as both have modern shoe components such as a heel counter, a cushioned midsole and an elevated heel. In contrast, to mimic barefoot running, minimalistic shoes which are characterized as having a flexible or no heel counter and a low heel elevation (less than 5 mm) have been developed.[10]

As the shoe type is associated with changes in kinematics, kinetics and muscle activity during locomotion,[11,12] habitual use of a

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specific type of shoe may also cause morphological adaptations in foot soft tissues. Morphological changes of both muscle and tendon have been documented in response to altered loading patterns. For instance, increased muscle volume, muscle fascicle length, muscle fascicle pennation angle[13] and connective tissue adaptations[14] have been reported after training interventions. Additionally, the cross-sectional area and stiffness of tendon were reported to be increased following high-loading training interventions.[15] Clearly, both muscles and tendons are highly dynamic tissues. Therefore, foot soft tissue morphology might adapt to the altered loading patterns imposed by wearing a specific type of running shoes. In some cases, these specific morphological changes can be related to the risk of overuse injuries. For instance, decreased intrinsic foot muscle volumes were found in young adults with chronic ankle instability.[16] Thickening of the plantar fascia and Achilles tendon is associated with plantar fasciitis and Achilles tendinopathy respectively[17,18] and a thinner heel pad, which is located underneath the calcaneus, was found in children with plantar heel pain, compared to children without pain.[19] Therefore, it is important to examine if the running shoe type is associated with the morphological differences in foot soft tissues.

Several longitudinal studies have been conducted to determine the effects of training in minimalistic shoes on foot muscle morphology, as minimalistic shoes are promoted to strengthen the foot muscles. The sizes of the abductor hallucis, flexor digitorum brevis and abductor digiti minimi were increased after 10–12 weeks of running in minimalistic shoes.[20,21] These findings indicate that running with less supportive shoes, e.g. minimalistic shoes, can increase the size of intrinsic foot muscles. There are, however, few studies to examine the effects of other running shoes on the morphology of foot soft tissues. Runners, who are prone to overuse injuries associated with excessive lower limb motions, are often recommended to use motion control shoes or custom-made insoles.[8,9] Investigating the soft tissue morphology in runners habitually using these shoes and/or insoles may provide insight into injury prevention.

Therefore, the aim of the current study was to determine the association between habitual running shoe type and the morphology of foot soft tissues in healthy recreational runners. The morphology of selected intrinsic and extrinsic foot muscles, the plantar fascia, Achilles tendon and heel pad was compared between four groups of runners using different running shoe types (neutral shoes, motion control shoes, minimalistic shoes and neutral shoes with insoles). The movement restriction and cushioning provided by conventional running shoes may reduce the workload of foot muscles, and thus may potentially weaken these muscles. Therefore, we hypothesized that runners using minimalistic shoes would demonstrate larger foot muscles and thicker tendons compared to those using other shoes, and that runners using motion control shoes and neutral shoes with custom-made insoles would be associated with smaller foot muscles and thinner tendons.

2. Methods

Based on an a priori sample size calculation ($\alpha = 0.05$, $\beta = 0.2$) from the cross-sectional area data of abductor hallucis and flexor digitorum brevis reported by Miller et al.,[21] 7 participants per group were needed to detect differences in foot muscle morphology between shoe groups. Thirty-eight healthy recreational runners participated this study. Ethical approval was obtained from the Medical Ethics Committee of KU Leuven. All participants provided written informed consent prior to their participation. The inclusion criteria were a running volume of at least 10 km per week, and age between 18 and 50 years old. Moreover, participants had to have been running with the same pair of shoes and/or insoles for at least 6 months, and have no running-related injuries in the 6 months prior to testing. A running-related injury was defined as any musculoskeletal complaint of the lower extremity which caused the runners to stop running for at least seven days.

To identify the runners' foot type, the Foot Posture Index (FPI) of each participant was obtained to distinguish a neutral foot posture from a pronated or supinated one.[22] By measuring truncated foot length (from the heel to the first metatarsophalangeal joint) and arch height at 50% of total foot length in a single-leg standing and sitting position, an arch height index as well as a relative arch deformation index was determined. For the single-leg standing measurement, participants were asked to stand on their right foot, with the left foot gently resting on an elevated plate (about 10 cm of height) to maintain balance. The arch height index was calculated as the arch height at 50% of the total foot length divided by truncated foot length during single-leg standing.[8] The relative arch deformation index was obtained by dividing the difference between the unloaded arch height (sitting position) and the arch height during single-leg standing by the unloaded arch height, and then multiplying this value by 10^4 divided by body weight.[21]

To identify shoe type, we followed the shoe assessment methodology described by Barton et al.[23] The age of the shoe and frequency of wear were based on participants' self-report. Shoe mass, heel height and heel-forefoot drop were measured. Motion control properties, including heel counter stiffness and sole rigidity (midfoot sole sagittal and frontal stability), were assessed, with the categories minimal (>45°), moderate (<45°), or rigid (<10°).[23] The four shoe conditions were: (1) neutral shoes characterized by a single midsole material, cushioning properties and a heel counter; (2) motion control shoes characterized by dual midsole material with stiffer material on the medial side and a stiff heel counter; (3) minimalistic shoes characterized by minimal cushioning, more flexible soles and no heel counter; (4) neutral shoes and custom-made insoles with a heel cup, arch support and cushioning properties. Detailed shoe properties are listed in Table 1.

An ultrasound system (a Telemed Echoblaster 128 CEXT system, UAB Telemed, Vilnius, Lithuania) was used to capture images of different foot structures using a 10 MHz linear wideband array transducer (model: HL9.0/60/128Z). All images were obtained by a trained assessor, who was blinded regarding the group category. Images of the intrinsic foot muscles (abductor hallucis (AbH), flexor hallucis brevis (FHB), flexor digitorum brevis (FDB)), and extrinsic foot muscles (flexor digitorum longus (FDL), tibialis anterior (TA) and the peroneus longus and brevis (PER)) were captured for morphological measurements, i.e. thickness and cross-sectional area (CSA). The CSA of TA was not measured because of insufficient width of the ultrasound probe used in the study. Moreover, ultrasound images of the following soft tissue foot structures were captured: the plantar fascia (PF) at its proximal, middle and distal part; the Achilles tendon (AT) at its calcaneal insertion site; and the heel pad. All scans for each participant were taken on the right foot. We followed the procedure for ultrasound measurements of foot structures described by Crofts et al., as their method showed excellent reliability.[24] Our pilot study on five participants using the same method also showed good intra-rater reliability, with Intraclass Correlation Coefficients (ICC) ranging from 0.88 to 0.97.

ImageJ software (National Institutes of Health, Bethesda, MD, USA) was used to measure the thickness and/or CSA of the selected soft tissues. The differences in participants' demographic characteristics, arch index, foot soft tissue morphology (thickness and CSA) between shoe groups were analyzed using a one-way ANOVA. Running volume data was not normally distributed (Shapiro–Wilk test), and thus a non-parametric test (Kruskal–Wallis test) was performed. A p-value of <0.05 was used as an indication of statistically significant difference. Effect sizes (Cohen's d) for soft tissue morphology differences were calculated between groups. The 95%

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