ASSOCIATIONS BETWEEN EXERCISE-INDUCED FLATTENING OF FOOT ARCH AND FATIGUE OF EXTRINSIC AND INTRINSIC FOOT MUSCLES

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We aimed to examine the associations between exercise-induced flattening of the foot arch and fatigue of extrinsic and intrinsic foot muscles. Fifteen male participants repeated 100 hops/set until they could no longer maintain the hop frequency or had completed 30 sets. The sagittal plane range of motion (ROM) of the midfoot during stance phase significantly decreased at the final set compared to the initial set (-8.8°). After the fatigue task, MRI T_2 relaxation time in all measured extrinsic and intrinsic foot muscles significantly increased (17.2–37.4%); however, only its increase in the tibialis posterior (TP) correlated with the relative change in midfoot ROM (r = 0.684). These results suggest that fatigue of TP is associated with the occurrence of flattening of the foot arch. This study provides a clinical implication that monitoring midfoot kinematics can be used to assess the condition of TP.

KEYWORDS: foot biomechanics, multi-segment foot model, magnetic resonance imaging

INTRODUCTION: The human foot arch flattens with weight-bearing and then recoils as the load is removed during bouncing gait such as running and hopping. Such a spring-like function helps to attenuate impact forces and store/release elastic strain energy (Farris et al., 2019), but from a different perspective, the foot is exposed to repetitive stress leading to the risk of injuries that interfere with sports participation and daily activity (Taunton et al., 2002).
It is known that prolonged exercises such as long-distance running induce the transient flattening of the foot arch (Shiotani et al., 2020). As the foot arch is temporarily collapsed, its function is compromised, which may increase the risk of injuries (Michelson et al., 2002). However, the cause of the transient flattening of the foot arch has not been fully understood.
The current understanding is that the extrinsic and intrinsic foot muscles provide active supporting bases for the foot arch (Kelly et al., 2015; Thordarson et al., 1995). During prolonged exercises, these muscles can be fatigued as they repeatedly contract to support and recoil the foot arch. This can be one of the causes of the exercise-induced flattening of the foot arch. However, Farris et al. (2019) reported that blocking the tibial nerve to inhibit intrinsic foot muscles' contraction did not change the foot arch deformation. Additionally, the extrinsic and intrinsic foot muscles vary in their structures (e.g., line of action and physiological cross-sectional area: PCSA) and force-producing capacities (Kura et al., 1997; Ward et al., 2009). Thus, we hypothesised non-uniformity in the effect of muscle fatigue on the transient foot arch deformation. Substantiating this hypothesis would provide evidence to establish measures to assess the condition of the foot arch and arch-supporting muscles for injury prevention. To test our hypothesis, we examined the associations between exercise-induced flattening of the foot arch and fatigue of extrinsic and intrinsic foot muscles.

METHODS: Fifteen healthy and recreationally active males (age 23.2 ± 2.9 years, height 172.4 ± 5.0 cm, and body mass 64.2 ± 7.7 kg; mean ± standard deviation) with no foot deformity were recruited in this study. Participants were asked to perform the fatigue task consisting of 100 single-leg hopping exercises per set with a rest interval of 30 s between sets. Hopping frequency was set at 2.2 Hz with a digital metronome, and participants were asked to match the timing of their landing with the metronome beat. The fatigue task continued until participants could no longer maintain the provided hopping frequency or until they had completed a maximum of 30 sets.

Participants performed the fatigue task barefoot. Fourteen reflective markers, 9.5 mm in diameter, were secured to anatomical landmarks of the right foot in accordance with the Rizzoli multi-segment foot model (Leardini et al., 2007). The three-dimensional (3D) coordinates of the marker positions were recorded using a 9-camera motion capture system (Motion Analysis Corp., USA) at a sampling rate of 200 Hz. Ground reaction force was recorded using a force platform (Force Plate 9287C; Kistler, Switzerland) at a sampling rate of 2000 Hz which was synchronized with the motion data. Position coordinates of the markers were smoothed using a 4th order Butterworth low-pass digital filter with a cut-off frequency of 10-12 Hz based on residual analysis (Winter, 2009). The 3D midfoot (metatarsal-calcaneal segments) angle was calculated using the Cardan sequence (Wu & Cavanagh, 1995).
Before (pre) and immediately after (post) the fatigue task, the transverse relaxation time (T_2)-weighted (echo times: 25, 50, 75, and 100 ms) and T_1-weighted magnetic resonance imaging (MRI) for the lower leg (slice thickness: 5 mm, gap: 5 mm) and the foot (slice thickness: 5 mm, gap: 0 mm) were recorded with a 3-tesla MRI scanner (SIGNA Premier; GE Healthcare, USA). With repeated muscle contractions, intracellular and intramuscular events such as increased microcirculation in the muscle, accumulation of osmolytes (e.g., phosphate, lactate, and sodium), and increased intramuscular water content are observed (Saab et al., 2000). Since T_2-weighted imaging can provide information on the water content within the muscle, the change in T_2 value can be used as an index of muscle fatigue (Hata et al., 2019).
Obtained images were analysed with OsiriX software (Pixmeo, Switzerland). Region of interest (ROI) was drawn by manually tracing the border of the tibialis posterior (TP), flexor hallucis longus (FHL), flexor digitorum longus (FDL), peroneus longus and brevis (PER), abductor hallucis (ABH), flexor digitorum brevis (FDB), quadratus plantae (QP), and abductor digiti minimi (ADM) with reference to the T_1 images (Figure 1). The T_2 value was calculated for each muscle within ROI at the slice of their muscle belly. Care was taken to analyse the same slice between sessions and to exclude visible intermuscular blood vessels.

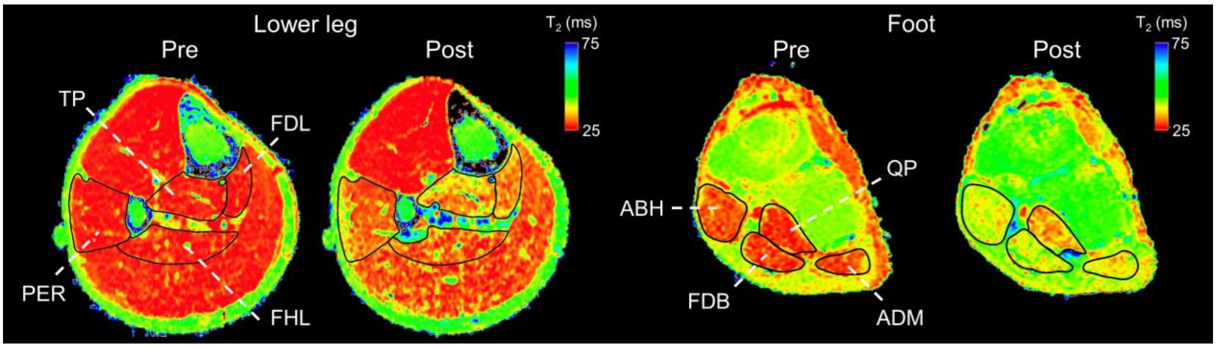

Figure 1: Examples of T_2 maps superimposed on T_2-MRIs for the lower leg and foot scanned at pre- and post-exercises. ROIs (black lines) were drawn with reference to T_1-MRIs. Red colours indicate lower T_2 values while bluer colours indicate higher T_2 values.

Using a paired *t*-test, the peak angle and range of motion (ROM) of the midfoot during the stance phase were compared between the averaged values of 11st–30th hops of the initial set and those of 71st–90th hops of the final set. The T_2 values of each muscle between pre- and post-fatigue task were compared using a paired *t*-test. To examine the associations between relative change from pre- to post-fatigue task in ROM of the midfoot (%ΔROM) and T_2 value (%ΔT_2) of each muscle, Pearson product-moment correlation coefficients were calculated.

RESULTS: Participants completed an average of 16 (range: 5–30) sets of the fatigue task. The midfoot ROM in the sagittal plane significantly decreased at the final set compared to the initial set ($p < 0.001$; Figure 2a) while the trajectory of the angular displacement was more flattened. At the final set, a significantly greater peak inversion ($p = 0.003$; Figure 2b) and smaller peak abduction ($p = 0.002$; Figure 2c) angle of the midfoot than at the initial set were found. The T_2 values in all measured extrinsic and intrinsic foot muscles significantly increased post-fatigue task when compared to pre-fatigue task (all $p < 0.001$; Figure 3a). %ΔROM in the sagittal plane was significantly correlated with %ΔT_2 of TP ($r = 0.684$, $p = 0.005$; Figure 3b), but not with the other extrinsic and intrinsic foot muscles (r = -0.195–0.132, all $p > 0.486$).

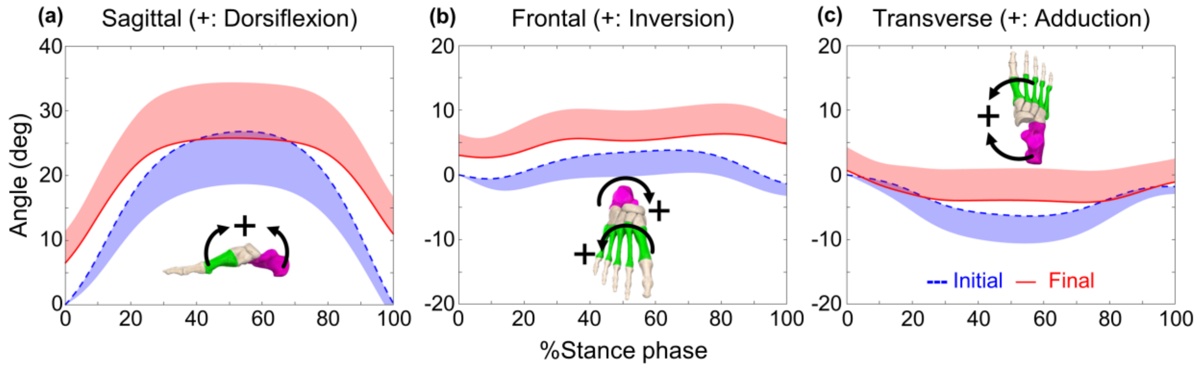

Figure 2: Ensemble averages of the midfoot angle in the sagittal (a), frontal (b), and transverse (c) planes during the stance phase of the initial (blue) and final (red) sets. The changes in the midfoot angle are shown relative to the angle just before the landing of the initial set.

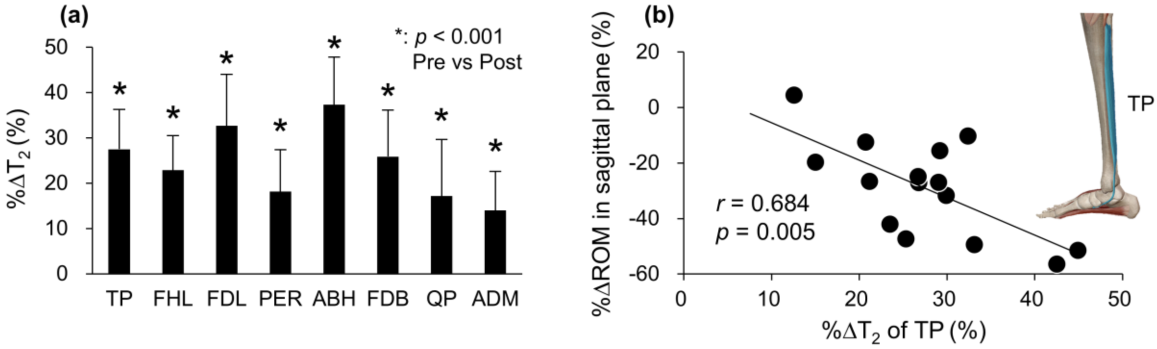

Figure 3: %ΔT_2 of each muscle between pre- and post-fatigue task (a) and the relationship between %ΔROM in the sagittal plane and %ΔT_2 of TP (b).

DISCUSSION: With repeated hopping exercises, the midfoot ROM in the sagittal plane decreased with a more rapid flattening and less recoil, indicating the transient flattening of the foot arch. Furthermore, only the increase in the T_2 value (an indication of muscle fatigue) of TP was correlated with the decrease in the midfoot ROM. These novel findings suggest that the fatigue of TP is associated with the occurrence of flattening of the foot arch. Among the extrinsic foot muscles, TP has the largest PCSA (Ward et al., 2009), thereby having a greater force-producing capacity to raise the foot arch (Thordarson et al., 1995). Moreover, it is known that TP dysfunction causes flatfoot deformity (Smyth et al., 2017). Our findings support the notion that TP plays a vital role in supporting the foot arch, and further add that the fatigue of TP is the key factor compromising the function of the foot arch.

The T_2 values of the other measured muscles increased; however, their changes were not correlated with the transient foot arch deformation. It has been reported that even when the contraction of the intrinsic foot muscles is prevented by a tibial nerve block, the foot arch deformation during exercises is not altered (Farris et al., 2019). Moreover, FHL, FDL, and PER have smaller PCSA with less contribution to raising the foot arch than TP (Thordarson et al., 1995; Ward et al., 2009). Our results were in line with these previous findings and supported our hypothesis. Although fatigue of these muscles might produce minor alternations in the bony structures within the foot (e.g., the Lisfranc and 1^{st}-5^{th} metatarsophalangeal joints), we suggest that they were not the determinants for the exercise-induced flattening of the foot arch.

In another viewpoint, our results provide a clinical implication that monitoring midfoot kinematics can be used to assess the condition of TP. Stress accumulation of TP affects the tibial fascial-traction that causes the symptoms of medial tibial stress syndrome (Bouché & Johnson, 2007), which is one of the major running-related injuries along with TP injury (Taunton et al., 2002). Moreover, transient flattening of the foot arch also leads to an increased risk of injury around the lower limb and foot (Michelson et al., 2002) and compromised athletic performance. For injury prevention, we suggest that it would be beneficial for athletes and their coaches to incorporate evaluating the midfoot kinematics (and/or navicular height; Shiotani et al., 2020) into their training and conditioning programs.

The midfoot ROM in the frontal and transverse planes were not significantly altered. However, the midfoot showed greater inversion and smaller abduction at the final set. Since the forefoot was constrained to the ground in the stance phase of hopping, this would result from greater calcaneal rotation in the frontal and transverse planes. These findings may be related to the changes of lower extremity joint kinematics in the frontal and transverse planes (e.g., greater ankle eversion, knee abduction, and hip adduction) throughout prolonged running (Willwacher et al., 2019). Such kinematic features are considered to be risk factors for sports-related injuries (Taunton et al., 2002). Thus, further analyses addressing the relationships between kinematic changes in the lower extremity and the midfoot are needed.

CONCLUSION: This study revealed that the exercise-induced flattening of the foot arch was associated with the fatigue of TP, but not with the other extrinsic and intrinsic foot muscles. Our findings support the notion that TP plays a vital role in supporting the foot arch, and further add the possibility that the fatigue of TP compromises the function of the foot arch. Furthermore, this study provides a clinical implication that monitoring the midfoot kinematics can be used to assess the condition of TP. Therefore, we suggest that it would be beneficial for athletes and their coaches to incorporate evaluating the midfoot kinematics into their training and conditioning programs for injury prevention.

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