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Effects of running-induced fatigue on plantar pressure distribution in novice runners with different foot types

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ABSTRACT

This study aimed to assess the effects of running-induced fatigue on plantar pressure parameters in novice runners with low and high medial longitudinal arch. Plantar pressure data from 42 novice runners (21 with high, and 21 with low arch) were collected before and after running-induced fatigue protocol during running at 3.3 m/s along the Footscan® platform. Peak plantar pressure, peak force and force-time integral (impulse) were measured in ten anatomical zones. Relative time for foot roll-over phases and medio-lateral force ratio were calculated before and after the fatigue protocol. After the fatigue protocol, increases in the peak pressure under the first-third metatarsal zones and reduction under the fourth–fifth metatarsal regions were observed in the low arch individuals. In the high arch group, increases in peak pressure under the fourth–fifth metatarsal zones after the running-induced fatigue was observed. It could be concluded that running-induced fatigue had different effects on plantar pressure distribution pattern among novice runners with low and high medial longitudinal foot arch. These findings could provide some information related to several running injuries among individuals with different foot types.

1. Introduction

Running is one of the most popular forms of exercise that contributes to sustained health and physical fitness [1]. Despite the benefits of running, not surprisingly various injuries have increased among the number of people who run regularly. Existing literature show that runners experience a variety of running-related injuries (RRI) such as overuse injuries [2,3]. Several studies have provided evidence that novice runners may be at increased risk of running-related injuries [3], the most common of these injuries occurring in the lower leg, knee and ankle [3]. Many of these injuries are associated with failure to maintain a physically active lifestyle [4].

Repetitive activities such as running, due to their cyclic nature create different levels of fatigue. Fatigue is a condition that is a factor in the incidence of running injuries [5]. During long-distance running, fatigue due to induced changes in kinematics and foot roll-over features lead to non-optimal mechanics of running [6–10]. Moreover, these changes can alter lower limb loading and therefore increase the risk of running-related injuries (RRI) and overuse injuries [11,12]. Other changes resulting from fatigue are change in plantar loading characteristics and foot pressure distribution [13,14]. The increased pressure under each foot region leads to different effects. For example, increasing the pressure under the metatarsal head region after fatigue may increase the risk of metatarsal stress fracture [13]. It is also noted that higher force impact under the second and third metatarsal heads is associated with patellofemoral pain syndrome [15].

The determinants of the RRI pattern can be referred to foot types [16]. Williams et al. [17] reported that high and low arch structure is associated with different injury patterns in runners. For instance, high-arched runners have a greater incidence of ankle injuries, bony injuries and lateral injuries, while low-arched runners exhibit more knee injuries, soft tissue injuries and medial injuries [17]. It is also reported that runners with low and high longitudinal arch structure have different running biomechanics [18]. Consequently, this difference is implicated as a factor that differentiates type of the individuals' injuries [19]. However, the influencing mechanism of foot type on RRI is not documented in the literature.

Despite the belief that fatigue and foot type are the most influential factors in increasing the risk of running-related injuries

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[5], previous studies have not clearly addressed the effects of running-induced fatigue among runners with different foot types. The purpose of this study was to compare the effect of running-induced fatigue on plantar pressure distribution in novice runners with low and high medial longitudinal foot arches during running. Data from this study can be useful in identifying the reason for different RRI development in individuals with different foot types.

2. Materials and methods

Forty-two novice heel-toe runners were categorized into two groups depending on their bilateral foot types namely, high (12 male, 9 female) and low medial longitudinal foot arch (13 male, 8 female). Demographic information for all subjects can be found in Table 1. The study was approved by the Research Ethics Committee of Hamedan University of Medical Sciences and all subjects gave informed consent.

All subjects were free of any cardiovascular pathology, neurological disorders, lower extremity injuries, foot or ankle surgeries; and none were overweight (BMI > 30).

Subjects were included in the study if they had either bilaterally low or high arch feet. According to Williams and McClay, the arch height index (AHI) was calculated by dividing the height of the dorsum by the truncated foot length (heel to first metatarsophalangeal joint). Runners with an arch ratio of at least 0.365 were considered high arch and those at most 0.275 were defined as low arch [20].

A novice runner was defined as a person who has been running less than 2–3 times per week for <45 min or <10 km, but they had the ability to run at a self-selected speed for approximately 30 min at a time [21].

All subjects were asked to run barefoot over a 14 m runway at a speed of 3.3 m/s ± 5% [22] while running speed was monitored by two sets of infrared photocells [22]. Running at this speed has previously been used for determining running related risk factors of injuries [22].

Before the measurements, all subjects performed training trials to become familiarized with the test situation. After familiarization, plantar pressure data were assessed during stance phases of running (6 trials) before and after running-induced fatigue.

A foot scan pressure plate (RsScan International, Belgium, 40 × 100 cm, 8192 sensors, 253 Hz) was clearly marked along the runway. The foot was automatically divided into the following ten anatomical zones by the software (Footscan1 software 7 Gait 2nd Generation, RsScan International): medial heel (HM), lateral heel (HL), midfoot, metatarsal first to fifth (M1-5), and the hallux (T1) and lesser toes (T2–5).

Subjects took part in a steady state running-induced fatigue protocol [20]. Each subject started walking on a treadmill (Horizon Fitness, Omega GT, USA) at a speed of 6 km/h. Subjects were asked to rate their perceived exertion by means of the 15-point Borg scale (6–20) [23] and were monitored for heart rate (Polar RS100, Polar Electro Oy, Woodbury, NY). Speed was increased in increments of 1 km/h every 2 min until an intensity of 13 on the Borg scale was reached. Subjects continued to run at the given steady state speed until a Borg score of 17 or 80% of maximum heart rate was reached, at which point they continued to run for 2 additional minutes [21]. Subjects then performed a cool-down at a self-selected speed. All subjects were provided with new neutral running shoes for the running-induced fatigue protocol [21].

The maximum pressure, peak forces (body weight %) and impulses (absolute force time-integral) were calculated for all ten anatomical zones before and after fatiguing. According to Willems et al. [14], for each trial, besides the total foot contact time, five distinct instants of foot rollover (Fig. 1) were determined including first foot contact (FFC, the instant the foot makes first contact with the pressure plate), first metatarsal contact (FMC, the instant one of the metatarsals contacts the plate), forefoot flat (FFF, the first instant all metatarsals make contact with the plate), heel-off (HO, the instant the heel region loses contact with the plate) and last foot contact (LFC, last contact of the foot on the plate) [14]. Based on these instants, total foot contact divided into four phases, namely initial contact phase (FFC-FMC), forefoot contact phase (FMC-FFF), foot flat phase (FFF-HO) and forefoot push-off phase (HO-LFC). Then, a medio-lateral force ratio $((T1 + M1 + HM) - (HL + M3 + M4 + M5)/(T1 + M1 + M3 + M4 + M5 + HM + HL))$ was calculated. In each phase the mean of this ratio was calculated [14]. The medio-lateral force ratio can range from −1 (pressure distribution laterally positioned) to +1 (pressure distribution medially positioned). The relative time for each phase was calculated.

Data were screened for normality of distribution using a Shapiro–Wilk test. The effects of fatigue on plantar pressure variables among high and low arch groups were analyzed with 10 (foot anatomical zones) × 2 (before and after fatiguing conditions) × 2 (groups) repeated-measures ANOVA test. Paired *t*-test was employed for within group comparison. Statistical analysis was performed at the $p \leq 0.05$ level. All statistical analyses were performed using SPSS software, Version 18.0 (SPSS Inc, Chicago, IL, USA).

3. Results

Repeated measures ANOVA revealed different effects of fatigue on the maximum pressure, peak force and impulse underneath the different zones among subjects. After fatiguing, maximum pressure was significantly increased underneath the first to third metatarsals ($p = 0.001$), while decreased for the fourth metatarsal ($p = 0.017$) and fifth metatarsal ($p = 0.012$) in the low arch group (Table 2). There was a significant increase in maximum pressure underneath the lateral heel, and in the fourth and fifth metatarsals ($p = 0.01$; $p = 0.001$ and $p = 0.001$ respectively) in the high arch group after the fatigue protocol. No significant changes were found for other foot anatomical zones (Table 3).

After the fatigue, peak force underneath the fourth metatarsal ($p = 0.021$) and toes 2–5 ($p = 0.001$) were significantly decreased, while there was increase in force underneath the first to third metatarsals (M1–3) in the low arch group. In the high arch group, fatigue increased the peak force underneath the M4 ($p = 0.01$), M5 ($p = 0.028$), midfoot ($p = 0.043$) and lateral heel ($p = 0.004$).

As Table 2 illustrates, the impulse underneath the M1-M3 zones significantly increased after fatigue in the low arch group, while fatigue decreased in the T2–5 areas ($p = 0.017$). Impulse for the

Table 1
Demographic information (mean ± standard deviation).

Group	Gender	*n*	Age (years)	Height (cm)	Mass (kg)	AHI
Low arch	Male	13	21.07 ± 2.95	179.07 ± 4.23	73.84 ± 7.3	0.264 ± 0.006*
	Female	8	25.25 ± 2.71	167.62	63.5 ± 6.458	0.257 ± 0.015*
High arch	Male	12	21.83 ± 3.24	182.91 ± 4.48	71.16 ± 4.38	0.419 ± 0.044
	Female	9	24 ± 1.32	172.55 ± 6.52	63.00 ± 4.35	0.409 ± 0.034

* AHI: Arch Height Index; * Indicates significant difference between low arch and High arch groups ($p < 0.05$).