

Research article

Plantar Pressures during Long Distance Running: An Investigation of 10 Marathon Runners

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Abstract

The objective of this study was to record plantar pressures using an in-shoe measuring system before, during, and after a marathon run in ten experienced long-distance runners with a mean age of 37.7 ± 11.5 years. Peak and mean plantar pressures were recorded before, after, and every three km during a marathon race. There were no significant changes over time in peak and mean plantar pressures for either the dominant or non-dominant foot. There were significant between foot peak and mean plantar pressure differences for the total foot ($p = 0.0001$), forefoot ($p = 0.0001$), midfoot ($p = 0.02$ resp. $p = 0.006$), hindfoot ($p = 0.0001$), first ray ($p = 0.01$ resp. $p = 0.0001$) and MTP ($p = 0.05$ resp. $p = 0.0001$). Long-distance runners do not demonstrate significant changes in mean or peak plantar foot pressures over the distance of a marathon race. However, athletes consistently favoured their dominant extremity, applying significantly higher plantar pressures through their dominant foot over the entire marathon distance.

Key words: Marathon running, in-shoe pressure insoles, plantar pressure, foot dominance.

Introduction

Running is a popular recreational activity, and the number of active participants has increased steadily over the past 10 years (Schueller-Weidenkamm, 2010). The foot is a complex structure that carries the body's weight and transmits impact to the ground during standing and walking (Ramanathan et al., 2010). During running the calculated vertical impact forces are approximately 2.5-2.8 times body weight (Cavanagh and Fortune, 1980), and muscle fatigue can significantly increase this vertical load further (Christina et al., 2001).

Despite the obvious fitness benefits associated with distance running, high impact loads are potentially responsible for many common running injuries. Although studies (Hintermann and Nigg, 1998; Willick and Hansen, 2010) have suggested a causal relationship between impact forces and injury, other studies (Hohmann et al., 2004; Schueller-Weidenkamm, 2010) were unable to confirm high impact forces result in a significant increase in running injuries.

In classical mechanics (Halliday and Resnick, 1978) Newton's first law of motion defines force as the vector sum of the mass of the body multiplied by its vector acceleration, and is therefore a vector quantity. In

sports science forces can be derived by measuring pressure per area. Pressure is therefore a scalar quantity, and as such is not dependent on direction but instead on magnitude. Pressure is commonly measured in gait analysis by either using force plates or in-shoe pressure monitor devices (Hennig and Milani, 1995).

To our knowledge only Nagel et al. (2008) have investigated plantar pressure before and after completing a marathon race. However, these authors concentrated on the metatarsal region and used a capacitive platform to measure plantar pressure with the athletes walking barefoot before and after the marathon. Given that no previous study has reported on between foot differences in plantar pressures of the different regions of the foot over the full distance of a competitive marathon run, it would be interesting to know whether foot pressures change over the entire distance of a marathon run, and whether fatigue has an influence on these pressures. Data obtained may help to understand long-distance running related injuries, and may also help to increase performance in these athletes.

The purpose of this study was, therefore, to record plantar pressures over five regions of the foot using an in-shoe measuring system before, during, and after a marathon race, and to specifically investigate the effect of fatigue on these plantar pressures.

Methods

Participants

Eight experienced recreational runners, and two semi-professional male runners participated in this study. All subjects were experienced athletes and had all been running consistently for a minimum of five years (Table 1). None of the athletes had any injuries 12 months prior to participation in this study. All participants provided written consent for this study.

All runners participated in an official marathon race and distances were measured according to the regulations of the International Association of Athletics Federations (IAAF). To guarantee similar conditions for all athletes, runners were only allowed to select from competitions with a flat course on asphalt with an overall altitude difference of less than 100 m over the race distance. To determine the dominant foot, the athletes selected which foot was used to kick a ball and which foot was generally used on the first step when approaching a flight of stairs (Lake et al. 2011).

Data collection

Plantar pressures

The medilogic Flex-Sohle shoe plantar pressure system (T&T medilogic Medizintechnik GmbH, Berlin, Germany) was used to measure plantar pressure. The system comes with a broad range of available inserts, and are specifically designed to fit different shoe sizes. Each insert itself consists of an array of 64 sensors (Figure 1) that are connected to a wireless transmitter via cables. Each sensor can measure pressures ranging from 0.6 to 64 $\text{N}\cdot\text{cm}^{-2}$. The medilogic system has been shown to have high intraclass-correlation-coefficients of 0.95 for repeatability and reliability in a two day x three repeated trial using six different pressures for 0-30 seconds (Koch et al., 2016; Price et al., 2014).

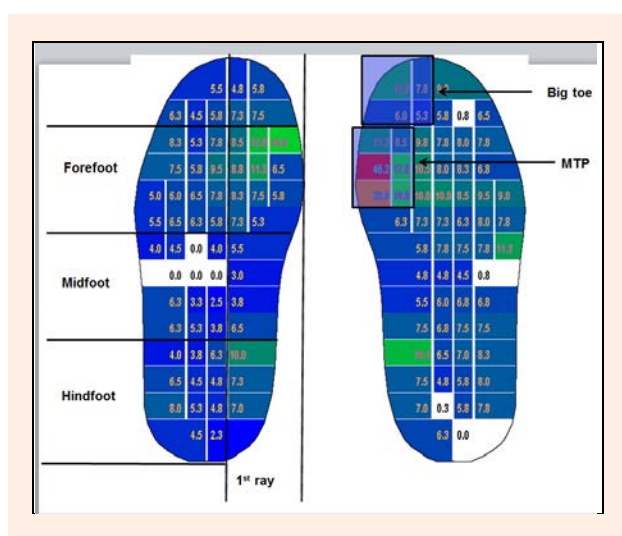


Figure 1. The medilogic Flex-Sohle shoe plantar pressure system (T&T medilogic Medizintechnik GmbH, Berlin, Germany) was divided into the following areas: hindfoot, midfoot, forefoot, first ray, big toe and first metatarsal-phalangeal (MTP) joint area.

Following an individually selected warm-up session the insoles were sized to fit each specific runner's shoe, and then placed into both shoes of the athlete prior to commencement of the marathon. Given the variety of sizing options all insoles were sized exactly to the sock liner and none of the participants reported any discomfort or influence on their running during the event. Running shoe selection was not controlled, and each athlete was allowed to use his preferred shoe in order to minimize discomfort or introduce changes in running style during the marathon race. It is recognized that this could potentially introduce bias; however, it was deemed more important to measure plantar pressures of each athletes "natural" environment. The cables were secured with medical taping/strapping along the posterior aspect of the lower extremity and connected to the transmitter secured to the athlete's lower back using a belt. The data for each sensor were sampled with a frequency of 300 Hz and transferred to the research associates' laptop computer via a wireless connection, mounted on a bicycle. Plantar pressures (in $\text{N}\cdot\text{cm}^{-2}$) were recorded over an interval of 60 seconds

before and after the run at the athlete's self-selected speed, and over the same 60 second interval every three kilometres during the 42.2km marathon. The self-selected running speed used during the warm-up session 30 minutes before the run was recorded, and this pace was used for plantar pressure measures during the run for the 60-second recording interval, as well as 10 minutes after completing the marathon race. Outside these plantar pressure measure intervals, all athletes were allowed to run at their self-selected speed. The research associate used the bicycle GPS computer to record "the before running speed" and paced the athlete at this speed during and after the race by cycling next to the athlete while monitoring and recording.

Peak pressures during each 60 second interval were recorded, and the mean pressure ($\text{N}\cdot\text{cm}^{-2}$) over the 60 second interval was calculated and used in subsequent data analysis. The peak and mean pressures of the subdivided areas (as described in the statistical analysis section), and the total pressure of the foot, were recorded. For standardization of data analysis both peak and mean pressures were divided by the athlete's body weight. This does not provide true correction for body weight, but does allow better between athlete comparisons (Table 2) while eliminating differences in body weight as a potential confounder during statistical analysis.

Physiological variables

Fourteen days prior to the marathon race all participants presented to the University's gait laboratory to establish their anaerobic threshold using a velocity-based protocol on a treadmill. Serum lactate ($\text{mmol}\cdot\text{L}^{-1}$), heart rate (bpm) and blood pressure were measured at the beginning, before each increase of speed, and one, three and five minutes after completion of the test. The anaerobic threshold was then determined by plotting lactate against heart rate, running speed, and blood pressure (Bentley et al., 2007).

Following the 60-second pressure recordings during the run, athletes were asked to stop for collection of serum lactate ($\text{mmol}\cdot\text{L}^{-1}$), and the pulse rate (bpm) was recorded from the provided heart monitor every three kilometres throughout the marathon. Athletes were also asked to verbally provide the 6-20 RPE Borg scale at these intervals to evaluate their individual perception of fatigue, and to determine whether changes in plantar pressure were related to fatigue (Chen et al., 2002). Serum lactate, heart rate and Borg scale values were measured both before and after completing the race.

Statistical analysis

For subsequent analysis of plantar pressures, the foot was divided into six anatomic areas: total foot, hindfoot, midfoot, forefoot, first ray, and first metatarsal head (MTP). Figure 1 demonstrates the selected division of the pressure insole. Descriptive statistics were determined for all continuous variables. Repeated measures of ANOVA were used to determine significant differences between intra-individual measurements for each anatomic area of the dominant foot. Paired samples-t-tests were used to compare the measured plantar pressures between the

dominant and non-dominant foot. A p-level of <0.05 was considered significant. All analyses were conducted using STATA SE (Version 12.0; StataCorp, College Station, Texas, USA) for Windows.

Results

Table 1 demonstrates the demographic details of all athletes. Table 2 and Figures 2-7 show the peak and mean pressures of both the dominant and non-dominant foot of the participants.

Table 1. Demographic details of all athletes.

	Weight (kg)	Height (m)	BMI ($\text{kg}\cdot\text{m}^{-2}$)	Age (yrs)	Arch type	Race time (hours)
1	70.0	1.87	20	29	normal	3:58
2	70.0	1.77	22.3	33	flat	4:19
3	68.0	1.76	22	39	flat	3:34
4	65.0	1.75	21.2	31	normal	3:46
5	66.5	1.71	22.7	37	normal	2:31
6	59.0	1.76	19	34	flat	4:11
7	67.0	1.67	24	59	normal	3:48
8	74.0	1.77	23.9	57	normal	3:54
9	68.5	1.77	21.9	33	normal	2:34
10	79.0	1.82	23.8	23	normal	3:28
Mean	68.7	1.77	22.1	37.5		
SD	5.3	.05	1.7	11.6		

Peak pressures

Statistical analysis revealed that there were no significant changes in foot peak plantar pressures of the dominant foot ($F = 1.7$, $p = 0.57$), peak pressures of the forefoot ($F = 2.84$, $p = 0.84$), midfoot ($F = 1.92$, $p = 0.6$), hindfoot ($F = 0.33$, $p = 0.34$), first ray ($F = 0.5$, $p = 0.93$), or first MTP ($F = 0.39$, $p = 0.56$). For the non-dominant foot, no significant changes in plantar pressures were observed over the duration of the event for the total foot ($F = 1.25$, $p = 0.24$), forefoot ($F = 1.75$, $p = 0.47$), midfoot ($F = 2.86$, $p = 0.1$), hindfoot ($F = 1.1$, $p = 0.35$), first ray ($F = 0.98$, $p = 0.48$), or the first MTP ($F = 0.96$, $p = 0.5$).

Mean pressures

For the dominant foot, statistical analysis revealed that

there were no significant changes over the duration of the marathon in mean plantar pressures of the total foot ($F = 2.21$, $p = 0.09$), forefoot ($F = 2.43$, $p = 0.4$), midfoot ($F = 1.59$, $p = 0.46$), hindfoot ($F = 3.1$, $p = 0.54$), first ray ($F = 1.0$, $p = 0.46$), and first MTP ($F = 0.33$, $p = 0.89$). For the non-dominant foot, similarly, no significant changes in plantar pressures were observed for the total foot ($F = 1.2$, $p = 0.24$), forefoot ($F = 2.01$, $p = 0.19$), midfoot ($F = 2.25$, $p = 0.08$), hindfoot ($F = 0.96$, $p = 0.46$), first ray ($F = 2.0$, $p = 0.14$) and first MTP ($F = 58$, $p = 0.88$).

Between feet differences

Peak and mean plantar pressures were significantly higher for the dominant foot (Table 2). There were significant between foot peak plantar pressure differences for the total foot ($F = 3.9$, $p = 0.0001$), forefoot ($F = 5.1$, $p = 0.0001$), midfoot ($F = 3.0$, $p = 0.02$) hindfoot ($F = 3.1$, $p = 0.0001$), first ray ($F = 3.1$, $p = 0.01$) and MTP ($F = 10.0$, $p = 0.05$). There were also significant between foot mean plantar pressures differences for the total foot ($F = 5.2$, $p = 0.0001$), forefoot ($F = 6.1$, $p = 0.0001$), midfoot ($F = 2.9$, $p = 0.006$) hindfoot ($F = 2.7.1$, $p = 0.0001$), first ray ($F = 3.1$, $p = 0.0001$) and MTP ($F = 6.6$, $p = 0.0001$).

Physiological variables

Table 3 demonstrates the mean heart rates, Borg scale values, and lactate serum levels for all participants before, during, and/or after the event. The mean heart rate increased significantly ($F = 97.99$, $p = 0.0001$) from km 3 to 42. There was also a significant difference ($p = 0.037$) between the before race and after race heart rate.

The lactate serum levels increased significantly ($F = 13.88$, $p = 0.0001$) from before the race to km 42. The most obvious (but non-significant) change was observed between km 39 and 42, from 3.3 to 5.05 ($\text{mmol}\cdot\text{L}^{-1}$). By the time the after race specimens were obtained the serum lactate level decreased to a mean of 3.66 ($\text{mmol}\cdot\text{L}^{-1}$); however, this was not significant ($p = 0.49$). The after race serum lactate level remained above the anaerobic threshold in 8 athletes, but the difference between the before race (1.44) and after race (3.66) levels was not significant.

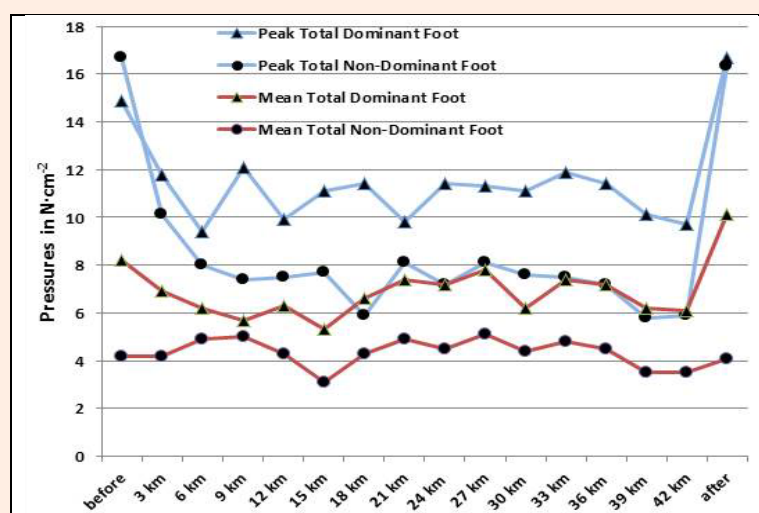


Figure 2. Peak and mean pressures of the total foot.

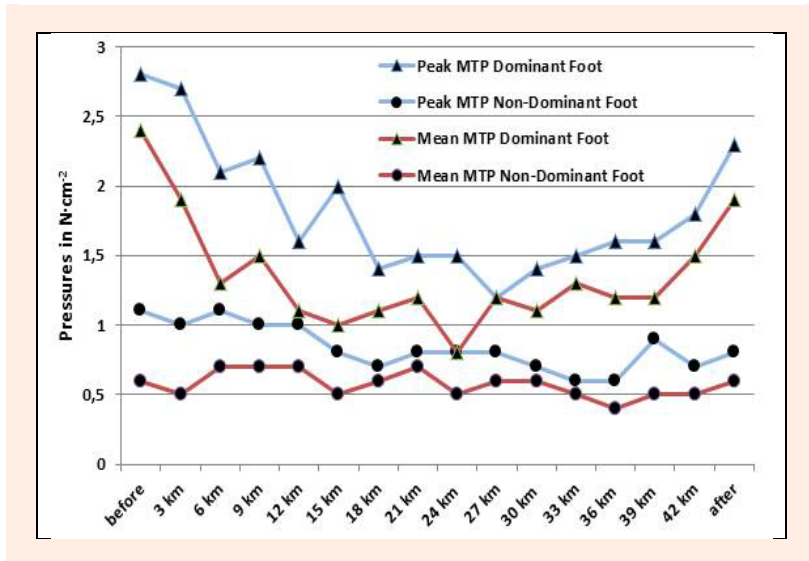


Figure 3. Peak and mean pressures of the metatarsal-phalangeal-anatomical region of the foot.

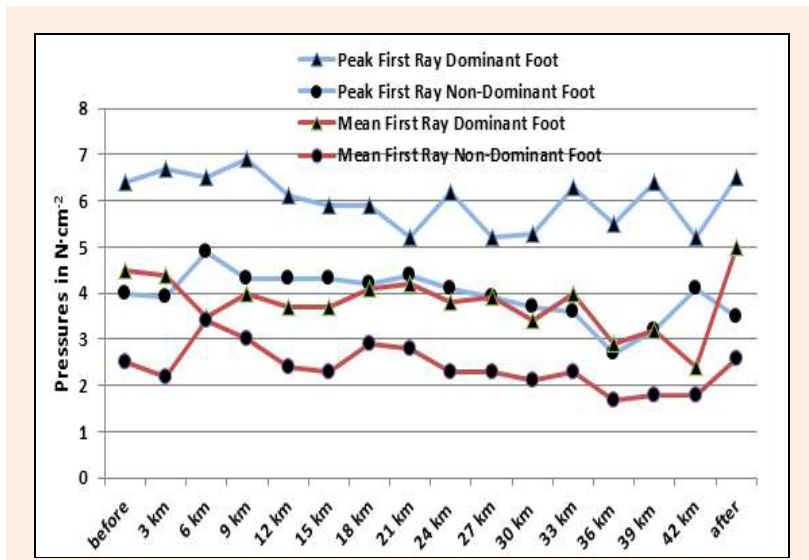


Figure 4. Peak and mean pressures of the first ray of the foot.

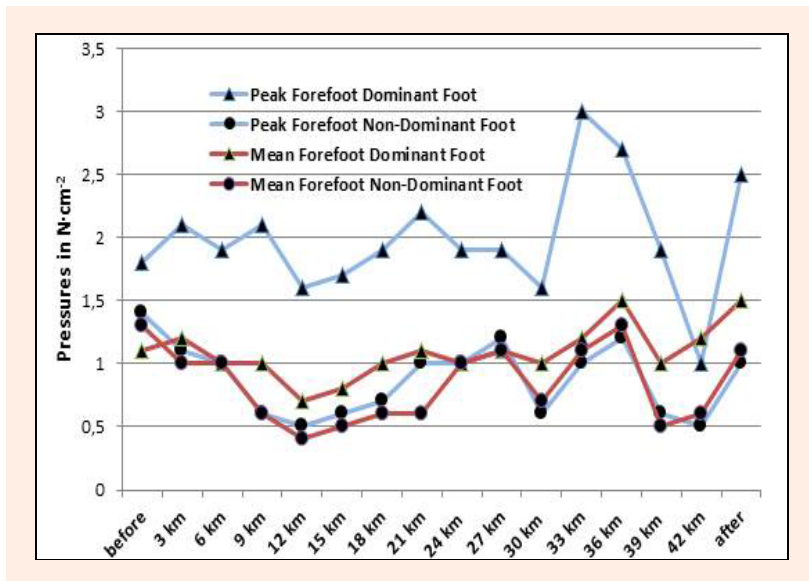


Figure 5. Peak and mean pressures of the forefoot region of the foot.

Table 2. Total peak and mean pressures (N/cm²) of the dominant and non-dominant foot of the individual participants before during and after the marathon run. Data are means (±SD).

	before	3 km	6 km	9 km	12 km	15 km	18 km	21 km	24 km	27 km	30 km	33 km	36 km	39 km	42 km	after
1*Total	14.9 (9.1)	11.8 (3.9)	9.4 (5.9)	12.1 (4.9)	9.9 (6.7)	11.1 (5.0)	11.4 (6.7)	9.8 (6.9)	11.4 (7.8)	11.3 (8.7)	11.1 (7.4)	11.9 (4.9)	11.4 (3.5)	10.1 (3.5)	9.7 (2.9)	16.7 (3.2)
2*Total	16.7 (1.4)	10.1 (8.1)	8 (4.4)	7.4 (2.4)	7.5 (2.4)	7.7 (3.6)	5.9 (3.1)	8.1 (4.7)	7.2 (4.5)	8.1 (4.7)	7.6 (4.0)	7.5 (3.1)	7.2 (2.5)	5.8 (2.2)	5.9 (1.6)	16.3 (2.6)
3*Total	8.2 (3.6)	6.9 (2.8)	6.2 (2.5)	5.7 (3.4)	6.3 (3.1)	5.3 (1.5)	6.6 (4.6)	7.4 (5.6)	7.2 (5.2)	7.8 (5.3)	6.2 (4.8)	7.4 (3.5)	7.2 (2.4)	6.2 (2.4)	6.1 (1.6)	10.1 (2.6)
4*Total	4.2 (1.3)	4.2 (2.8)	4.9 (2.4)	5 (2.5)	4.3 (1.7)	3.1 (1.4)	4.3 (1.7)	4.9 (3.3)	4.5 (3.2)	5.1 (3.3)	4.4 (2.5)	4.8 (2.3)	4.5 (1.6)	3.5 (1.4)	3.5 (1.4)	4.1 (1.5)
1* MTP	2.8(1.5)	2.7 (1.4)	2.1 (1.4)	2.2 (1.2)	1.6 (.8)	2 (1.2)	1.4 (.6)	1.5 (0.7)	1.5 (0.9)	1.2 (0.7)	1.4 (0.8)	1.5 (1.)	1.6 (0.9)	1.6 (1)	1.8 (1)	2.3 (1.5)
2*MTP	1.1 (.6)	1.0 (.6)	1.1 (1.0)	1.0 (.8)	1.0 (.7)	.8 0.5)	.7 (.4)	0.8 (0.5)	0.8 (0.5)	0.8 (0.3)	0.7 (0.3)	0.6 (0.2)	0.6 (0.2)	0.9 (0.3)	0.7 (0.4)	0.8 (0.7)
3*MTP	2.4 (1.5)	1.9 (1.4)	1.3 (.9)	1.5 (1.0)	1.1 (.8)	1.0 (1.0)	1.1 (.7)	1.2 (0.7)	0.8 (0.6)	1.2 (0.9)	1.1 (0.7)	1.3 (0.8)	1.2 (0.8)	1.2 (1)	1.5 (1)	1.9 (1.3)
4*MTP	.6 (.4)	.5 (.4)	.7 (.5)	.7 (.5)	.7 (.7)	.5 (.6)	.6 (.4)	0.7 (0.5)	0.5 (0.4)	0.6 (0.6)	0.6 (0.4)	0.5 (0.3)	0.4 (0.3)	0.5 (0.5)	0.5 (0.6)	0.6 (0.6)
1*first ray	6.4 (2.6)	6.7 (3.4)	6.5 (2.7)	6.9 (2.0)	6.1 (2.7)	5.9 (2.7)	5.9 (4.2)	5.2 (3.6)	6.2 (4.7)	5.2 (2.2)	5.3(3.9)	6.3 (3.8)	5.5 (3)	6.4 (3.2)	5.2 (1.5)	6.5 (2.6)
2*first ray	4 (1.2)	3.9 (1.2)	4.9 (3.5)	4.3 (1.4)	4.3 (1.8)	4.3 (1.9)	4.2 (2.0)	4.4 (1.9)	4.1 (2.6)	3.9 (2.3)	3.7 (2.2)	3.6 (1.2)	2.7 (1.6)	3.2 (1.5)	4.1 (4.8)	3.5 (0.8)
3*first ray	4.5 (2.4)	4.4 (2.1)	3.5 (2.3)	4.0 (1.6)	3.7 (1.7)	3.7 (1.7)	4.1 (4.8)	4.2 (2.9)	3.8 (2.8)	3.9 (1.8)	3.4 (2.2)	4 (1.7)	2.9 (2)	3.2 (2.3)	2.4 (1.5)	5 (1.7)
4*first ray	2.5 (.5)	2.2 (.7)	3.4 (2.3)	3.0 (1.3)	2.4 (1.0)	2.3 (1.1)	2.9 (2.4)	2.8 (1.9)	2.3 (1.7)	2.3 (1.1)	2.1 (1.1)	2.3 (0.9)	1.7 (1.1)	1.8 (0.6)	1.8 (0.5)	2.6 (0.7)
1*forefoot	6.7 (2.6)	6.9 (3.2)	6.7 (2.6)	5.4 (3.1)	6.4 (2.5)	6.2 (4.2)	6.0 (3.3)	4.6 (3.2)	4.9 (3.5)	5.2 (4)	5.6 (4.8)	5.1 (4)	4.6 (2.5)	4.2 (1.6)	4.8 (1.5)	4.4 (1.3)
2*forefoot	3.1 (.8)	4.3 (2.9)	3.4 (1.6)	3.1 (2)	4.1 (2.4)	4.4 (2.8)	3.4 (1.9)	3.8 (2.4)	3.3 (2.2)	3.6 (2.7)	3.6 (1.9)	3.3 (1.4)	3 (1)	2.5 (0.9)	2.3 (0.9)	3.1 (1.7)
3*forefoot	4.9 (3.0)	4.3 (2.5)	3.1 (2.0)	4.3 (1.9)	3.8 (2.5)	3.0 (1.3)	3.6 (2.6)	3.9 (2.9)	3.8 (2.7)	4.1 (3)	3.6 (2.8)	3.6 (1.9)	3.2 (1.1)	3.2 (1.6)	3.2 (1.2)	5.8 (2.1)
4*forefoot	2.2 (8)	2.7 (2.4)	2.4 (1.2)	2.6 (1.3)	2.6 (1.5)	1.9 (.9)	2.3 (1.5)	2 (1.6)	2.2 (1.6)	2.2 (1.6)	2.3 (1.4)	2.2 (1.1)	1.8 (0.6)	1.8 (0.8)	1.3 (0.8)	2.3 (1.2)
1*midfoot	1.8 (.9)	2.1 (.4)	1.9 (.4)	2.1 (1.1)	1.6 (.8)	1.7 (.5)	1.9 (.7)	2.2 (1)	1.9 (0.8)	1.9 (1)	1.6 (0.8)	3 (1)	2.7 (1.7)	1.9 (0.9)	1 (1)	2.5 (0.9)
2*midfoot	1.4 (1.0)	1.1 (.8)	1 (1.0)	.6 (.4)	.5 (.2)	.6 (.3)	.7 (.3)	1 (0.3)	1 (1.1)	1.2 (1.5)	0.6 (0.3)	1 (0.9)	1.2 (1.1)	0.6 (0.3)	0.5 (0.3)	1 (0.9)
3*midfoot	1.1 (.4)	1.2 (.4)	1 (.3)	1.0 (.4)	.7 (.2)	.8 (.3)	1.0 (.4)	1.1 (0.5)	1 (0.5)	1.1 (0.6)	1 (0.4)	1.2 (0.5)	1.5 (0.8)	1 (0.4)	1.2 (0.6)	1.5 (0.5)
4*midfoot	1.3 (1.0)	1 (.8)	1 (1.1)	.6 (.3)	.4 (.2)	.5 (.2)	.6 (.4)	0.6 (0.3)	1 (1)	1.1 (1)	0.7 (0.4)	1.1 (0.8)	1.3 (1)	0.5 (0.2)	0.6 (0.2)	1.1 (1)
1*hindfoot	2.4 (1.2)	1.7 (.7)	1.5 (.7)	1.7 (.6)	1.7 (.5)	2.0 (.9)	2.3 (1.5)	2.8 (2.3)	2.2 (1.9)	3.1 (2.3)	3 (2.2)	3.7 (2.8)	3.4 (3.1)	2.6 (1.7)	2.6 (1)	4.1 (1.3)
2*hindfoot	1.3 (.3)	2.2 (1.3)	1.8 (1.3)	1.2 (.4)	1.4 (.4)	1.7 (.7)	1.9 (1.3)	1.9 (1.3)	1.7 (1.3)	2.3 (1.2)	2 (1.3)	1.9 (1)	1.7 (0.8)	1.6 (0.7)	2.2 (0.9)	2.2 (1.3)
3*hindfoot	1.5 (.8)	1 (.3)	.9 (.3)	.9 (.3)	1 (.3)	.9 (.9)	1.3 (1.4)	1.5 (1.3)	1.5 (1.3)	1.8 (0.8)	1.5 (1.4)	2 (1.6)	2 (1)	1.6 (0.4)	1.4 (1.2)	2.5 (1.3)
4*hindfoot	.8 (.3)	1.2 (1.2)	1 (1)	.6 (.2)	.6 (.2)	.8 (.5)	1.0 (.8)	1 (0.8)	1 (0.8)	1.3 (0.8)	1 (0.5)	1.3 (0.8)	1.2 (0.8)	0.8 (0.4)	1.3 (1.2)	1.5 (1.3)

1* peak pressures of the dominant foot and 2* the non-dominant foot; 3* mean pressure of the dominant foot and 4* the non-dominant foot.

Table 3. The physiological characteristics mean (SD): heart rate in rpm/min; lactate serum levels in mmol·L⁻¹. Data are means (±SD).

	before	3 km	6 km	9 km	12 km	15 km	18 km	21 km	24 km	27 km	30 km	33 km	36 km	39 km	42 km	after
Heart rate	69 (7)	130 (17)	138 (11)	140 (8)	142 (9)	143 (9)	143 (8)	145 (9)	147 (11)	147 (10)	148 (11)	150 (10)	151 (10)	156 (9)	168 (10)	104 (18)
Borg scale		7.1 (1.3)	7.5 (1.5)	8 (1.2)	8.5 (1.7)	9.1 (1.6)	9.6 (1.3)	9.9 (1.6)	10.4 (1.4)	11. (1.3)	11.3 (1.5)	12.3 (1.6)	13 (1.9)	13.9 (2.4)	15.2 (2.1)	
Lactate*	1.4 (.4)	1.7 (.8)	1.6 (.7)	1.6 (.8)	1.7 (.7)	1.9 (.9)	1.7 (.8)	1.9 (.8)	1.8 (.6)	1.9 (.8)	2.0 (.9)	2.6 (1.3)	2.5 (1.2)	3.3 (1.6)	5 (2.1)	3.7 (1.8)

*mean anaerobic threshold 2.9 ± 0.7 mmol·L⁻¹.

The Borg scale mean values increased significantly (F = 6.27, p = 0.0001) from km 3 to km 42. Although the mean within group values increased slowly and steadily during the marathon, the Borg scale value increased by 1.4 points between km 39 and 42. This subjective increase was not accompanied by increases in mean heart rate, but

instead a non-significant increase in serum lactate levels from 3.3 to 5.05 (mmol·L⁻¹) was observed. Eight of the runners were performing above their anaerobic threshold at km 42, a fact that could explain the subjective perception of fatigue.

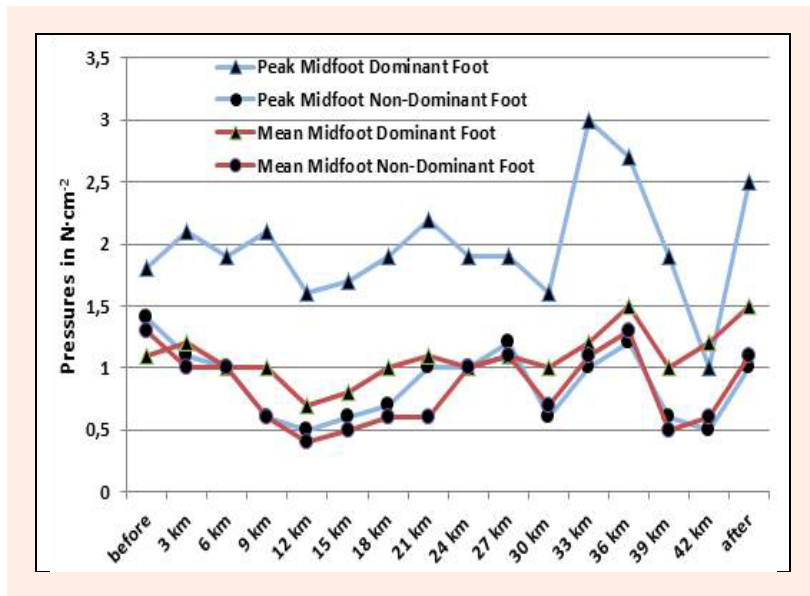


Figure 6. Peak and mean pressures of the midfoot region of the foot.

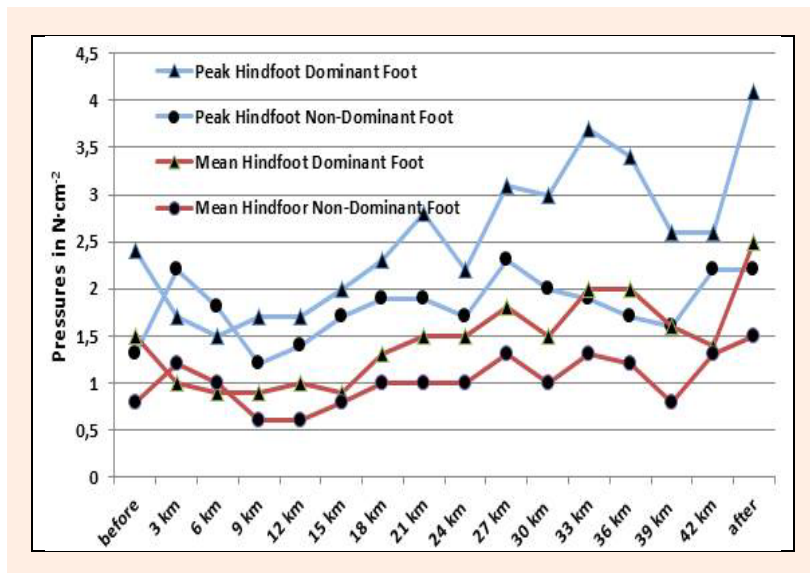


Figure 7. Peak and mean pressures of the hindfoot region of the foot.

Discussion

The results of this study indicate that long-distance runners do not demonstrate significant changes in mean or peak plantar foot pressures over the distance of a marathon race, for either the dominant or non-dominant foot. However, all runners demonstrated significant between foot plantar pressures favouring the dominant foot over the entire marathon distance.

To our knowledge, this is the first study to investigate peak and mean plantar pressures before, during, and after a competitive marathon race in both recreational and semi-professional runners. Previously, Karagounis, et al. (2009) examined plantar pressure in ultra-marathon runners before, immediately following, and 24 hours after a spartathlon race. They demonstrated a significant increase in peak pressure in the forefoot and a decrease under the toes both pre- and immediately after the race, with com-

plete recovery of all plantar pressures within 24 hours after the ultra-marathon. Alfuth and Rosenbaum (2011) investigated plantar pressures during a 10 km run, but did not observe any significant changes over time in either parameter. While their results support our findings, they do not provide a satisfactory explanation for these results.

Typically, plantar pressures during running have been documented to be highest under the heel and metatarsal heads, with a shift in pressure to the central and medial areas of the foot through various phases. Willson and Kernozek (1999) showed a significant reduction in heel loading with an increase in medial metatarsal loading, and hypothesised that these decreased values could be associated with a decreased step length beginning at the heel during running. Willems, et al., (2012) recently demonstrated increases in forefoot, midfoot, and medial heel loading, with concomitant decreased loading of the lateral toes during running. Earlier, Nagel et al., (2008)

investigated plantar pressures below the metatarsal heads before and after a marathon run in 200 athletes. They observed significantly increased loading patterns after the race, and suggested that these increased loading patterns could contribute to stress fractures. However, the authors performed the investigation in barefoot walking athletes, and their results have to therefore be viewed critically.

It has also been suggested by several researchers that both impact force and loading rate are related to stride length, cadence, and vertical ground reaction forces and knee flexion angle at heel strike (Clarke et al., 1985; Nigg et al., 1987; Hardin et al., 2004). Nigg, et al. (1987) has proposed that runners change their technique in response to potentially harmful loads and keep the impact forces constant. Clarke, et al. (1985) reported that runners can change stride length and stride rate most easily. As a consequence, vertical impact forces are reduced on the lower extremity. Hardin et al. (2004) has noticed that runners adapt their kinematics as a reaction to different footwear characteristics, running surface, and duration of the activity. Increased midsole shoe hardness resulted in greater peak ankle dorsiflexion velocity; increased surface stiffness resulted in decreased hip and knee flexion at contact; and with increased duration, hip flexion at contact decreased, plantarflexion at toe-off increased, and peak dorsiflexion and plantarflexion velocity increased. However, different study designs, such as use of a treadmill compared to outdoor running, differences in distance, speed, shoes, running style, and insoles versus forceplates, makes it difficult to compare findings between these studies.

Running speed and foot type have previously been suggested to influence plantar pressures during long-distance running. Chuckpaiwong, et al., (2008) described an increase of foot contact area and significant increases in peak pressure over the period of a longer run. Earlier, Segal, et al. (2004) demonstrated that the hallux and hind-foot region had the highest plantar pressures, and these increased linearly with faster speeds. The lateral forefoot had the lowest overall peak pressures, and this decreased with faster speeds. Sneyers, et al. (1995) investigated the influence of foot types on plantar loading pressures, and demonstrated significant differences in loading patterns for individuals with a normal foot, flat foot, and high arched foot. The plantar heel load was distributed significantly more toward the anterior part of the calcaneus in the pes planus group compared with the normal group.; the relative load under the midfoot region was significantly lower in the pes cavus group compared with the other foot types; and the relative load on the forefoot was significantly higher in the pes cavus group and lower in the pes planus group. However, they were unable to demonstrate any difference between the dominant and non-dominant foot.

In contrast to the above studies, we could not demonstrate any significant changes in plantar pressures measured every 3 km in experienced and trained runners during a competitive marathon. While we have not specifically controlled for foot type in the present study, three of the runners had a flatfoot and seven runners a normal arch. The athletes in our project also ran at different self-

selected speeds; however we have strictly controlled running speed during the intervals, that foot pressure was recorded. Despite these measures, we would have expected changes in plantar pressures to be observed in our cohort. Ferris, et al. (1999) provides a possible explanation for why we have not observed these changes as described in earlier research. They examined adaptations in leg stiffness when runners suddenly encountered different running surfaces, and noticed rapid adjustments. Ferris, et al. (1999) believe these adjustments are due to the rapid modulation of neural pathways caused by stretch reflex responses within athletes, using either pre-synaptic inhibition or fusimotor action as previously described by Stein and Capaday (1988).

Wiegerinck, et al. (2009) suggested that running shoes have an influence on loading patterns, and examined differences between training shoes and racing flats; they demonstrated significantly higher maximum force and peak pressures in the racing flats. Marathon runners, whether recreational athletes or professional runners, have to undergo extensive preparation for the event, and obviously develop neuro-muscular pathways during training which allow them to control loading patterns in an efficient manner over the full distance of a 42.2 km marathon. Furthermore, athletes who are able to compete in a marathon may have undergone natural selection and may be genetically advantaged. Recreational runners who do not have the ability or genetic constitution to perform long-distance, high impact activities may simply be unable to undergo intensive training without injury and voluntarily cease this perceived unhealthy, painful activity.

Bus (2003) previously demonstrated that older runners, such as those involved in the present study, adjust their gait patterns by lowering speed and decreasing their stride length as a physiological adjustment, and thereby reduce peak impact forces and maximal loading rates. A reduction of self-selected running speed is thus a useful strategy to reduce impact forces. Keller, et al. (1996) has previously shown that impact forces increase up to the individual's normal jogging speed, but remain constant at approximately 2.5 times body weight. We have specifically controlled for running speed during the test intervals, it would be a reasonable assumption that participants were not able to use these same strategies to control for impact forces during this experiment.

Previous studies have suggested that fatigue does have a significant effect on plantar pressures. Biseaux and Moretto (2008) demonstrated a significant decrease in plantar pressure on both the heel and the midfoot during a 30-minute intensive run, along with a significant increase in peak pressure and relative impulse under the forefoot. After a 30-minute rest, the heel and forefoot loading remained significantly affected compared to the pre-test conditions, while variability, step length, and frequency remained unchanged. Christina, et al. (2001) reported that localized muscle fatigue of the foot and ankle invertors and dorsiflexors have a significant effect on loading rates. Weist, et al. (2004) demonstrated a significant increase with fatigue of the peak pressures, maximal forces, and impulses under the forefoot and the medial midfoot, but could not find a correlation with foot type.

In the present study we measured fatigue both subjectively (with the valid and reliable Borg Scale) and objectively (using the physiological parameters of heart rate and serum lactate levels). The purpose of these measures was to enable us to compare the marathon running intensity with the anaerobic threshold of each athlete as tested prior to each marathon race. In contrast to the previous findings, fatigue did not influence plantar pressures in our study cohort, with all of the runners exhibiting intensities below their anaerobic threshold. Previous researchers have provided a plausible explanation for our findings of no changes in plantar pressures over the course of a marathon run. When fatigue does occur, runners tend to change stride rate and stride length (Clarke et al. 1985), run with a faster cadence (Willson et al., 1999) and increase knee flexion during ground contact (Derrick, 2004); using any of these strategies will lead to decreases in impact forces (Bus, 2003). The use of different running shoe types amongst the participants may have resulted in different plantar pressure measurements. However, Clinghan et al. (2008) showed no significant differences in measured plantar pressures between low- and medium cost running shoes across three different brands. It could therefore be safely assumed that the individual running shoe used by our participants was unlikely to influence the current results. The principal limitation of this study is that sensor creep and temperature differences during the study period could have influenced plantar pressure data. Arndt (2003) has demonstrated that pressure sensor values range from 8-17% over a three hour walk on two different occasions using a Pedar® insole. In contrast, Hurkmans et al. (2006) could not demonstrate any significant changes over a seven hour testing period. Currently the effect of temperature on the force output of the medilogic® insoles is still unclear (Koch et al., 2016) and an increase of temperature in the running shoe could have possibly resulted in bias. However, one would expect a steady increase of foot temperature resulting in a similar change of pressure data, which was not observed in any of the athletes.

Conclusion

The results of this study suggest that long-distance runners do not demonstrate significant changes in mean or peak plantar foot pressures over the distance of a marathon race, for both the dominant and non-dominant foot. However, significantly higher plantar pressures were observed for the dominant foot over the entire marathon distance, suggesting that athletes consistently favoured weight-bearing on their dominant extremity.

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Key points

- Fatigue does not increase foot pressures
- Every runner has a dominant foot where pressures are higher and that he/she favours
- Foot pressures do not increase over the distance of a marathon run

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