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EFFECT OF THE DISTANCE RUN AND THE REST PERIODS ON THE STATIC PLANTAR PRESSURE DURING A 24-HOUR RUNNING RACE

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ABSTRACT

Long-distance running has been a popular activity for decades. Beyond physical and physiological demands on runners, the lower limbs and the feet are affected in terms of their function. The aim of this study was to monitor plantar pressure over the course of a 24-h long-distance run. Twelve experienced runners participated in the study. Plantar pressure measurements were performed prior to the start of the race and regularly during the race. Rest periods and walking periods were recorded. The correlation coefficient between the ratio between the forefoot and the rearfoot and the relative distance run indicates a negative correlation; the longer the distance run, the lower the ratio between the forefoot and the rearfoot. Pressure is transferred preferentially to the rear-foot irrespective of the increase in pressure around mid-race by periods of rest and walking. Monitoring of the plantar pressure and the plantar surface area throughout the long-distance race indicated a non-linear progression of these parameters that are not in keeping with a type of deterioration. Although some of the results may contribute to the development of running injuries, our study describes a dynamical adaptation to protect against pain and the consequences of load impacts.
Keywords: long-distance running, load impact, plantar surface area, dynamical strategy

EFECTOS DE LA DISTANCIA RECORRIDA Y DE LOS PERIODOS DE DESCANSO EN LA PRESION PLANTAR ESTATICA DURANTE UNA CARRERA DE 24 HORAS

RESUMEN

La carrera de larga distancia ha sido una actividad popular durante décadas. Más allá de las exigencias físicas y fisiológicas de los corredores, las extremidades inferiores y los pies se ven afectados en términos de su función. El objetivo de este estudio fue monitorizar la presión plantar en el transcurso de una carrera de larga distancia de 24 horas. Doce corredores experimentados participaron en el estudio. Las mediciones de presión plantar se realizaron antes del inicio de la carrera y regularmente durante la carrera. Se registraron periodos de descanso y caminatas. El coeficiente de correlación entre la relación entre el antepié y la parte posterior del pie y la distancia relativa recorrida indica una correlación negativa; cuanto mayor sea la distancia recorrida, menor será la relación entre la parte delantera del pie y la parte posterior del pie. La presión se transfiere preferentemente al pie trasero, independientemente del aumento de la presión alrededor de la mitad de la carrera por períodos de descanso y caminata. La monitorización de la presión plantar y el área de la superficie plantar a lo largo de la carrera de larga distancia indicó una progresión no lineal de estos parámetros que no se corresponden con un tipo de deterioro. Aunque algunos de los resultados pueden reflejar un desarrollo de las lesiones por correr, nuestro estudio describe una adaptación dinámica para proteger contra el dolor y las consecuencias de los impactos de la carga.
Palabras clave: carrera de larga distancia, impacto de carga, superficie plantar, estrategia dinámica

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INTRODUCTION

Long-distance running has been a popular activity for decades. Whereas health and well-being are the main motivational factors for recreational running, there is also strong interest in competitive running. Aside from the competitive events themselves, training also–out of necessity–places increased physical and physiological demands on runners. Although the implications have been studied particularly in regard to their physiological and metabolic aspects, it is generally acknowledged that the repeated impacts with running affect the lower limbs and feet in terms of their function (Hohmann, Wörtler, & Imhoff, 2004; van Gent et al., 2007; Willick & Hansen, 2010).

Previous studies have highlighted the effect of running on plantar pressure (Nagel, Fernholz, Kibele, & Rosenbaum, 2008). Thus, it has been reported that the ratio between the mean forefoot and the mean rearfoot pressure is higher after having run a marathon than before, thereby indicating that the load on the forefoot is higher than that on the rearfoot. This increase in loading of the metatarsal heads appears to be consequent to a load shift from the toes and modification of the running pattern during the race due to fatigue. This may be linked with knee kinematics. To reduce the impact force during ground contact, knee flexion is increased, which could explain the forefoot overload (Derrick, 2004). Nagle et al. (2008) have suggested that such a mechanism could explain the risk of stress-induced fatigue fractures of the metatarsals in runners; loading of the forefoot associated with decreased function of the toes to avoid loading force on the lower limbs (Willems, De Ridder, & Roosen, 2012).

These previous studies were done during marathon races, which cover a distance of 42.195 km. Whereas the mean duration of the race was not indicated by the authors, the usual time for a recreational runner to cover the distance of a marathon does not exceed 5 hours. Moreover, during such a running race, rest times are not allowed. On the other hand, during an ultra-running race, which can exceed 100 km (Hoffman, Ong, & Wang, 2010; Knez, Coombes, & Jenkins, 2006), runners can incorporate rest strategies to recover physiological (Millet, 2011) or psychological determinants (Simpson, Post, Young, & Jensen, 2014). For example, when faced with a loss of muscle strength due to the race and the consequent muscle fatigue, and to counter sleep deprivation, runners can reduce their speed. This places less mechanical stress on the muscles, thereby precluding a degree of recovery (Saugy et al., 2013). Thus, reduced speed or rest periods can alter plantar pressure, particularly in terms of the load distribution. In such conditions, the theoretical linear regularity of the running speed could provide a point of reference and highlight different race strategies.

The aim of this study was to analyse the progression of plantar pressure relative to the distance run over the course of a 24-h running race.

METHOD

This study was carried out in accordance with the 2013 Helsinki Declaration regarding ethical principles for medical experimentation using human beings, and it was approved by the local ethics committee.

The experiment took place during the French National 24-h championship. The participants ran on a 1 km flat track. The experimental device was placed next to the track.

Participants

Twelve adults (6 males and 6 females) participated in the study (Table 1). They all competed regularly in long-distance races and had previously participated in at least one 24-h race. None of the participants suffered from any type of pain or orthopaedic or neurological problem in the lower limbs at the time of the experiment. Individual anthropometric data were acquired. They volunteered to participate in the study and they provided written consent.

In accordance with Hohmann et al. (2016), the dominant foot was determined as the one the runners use to kick a ball and it was the foot that they generally use on the first step of a flight of stairs.

Procedure

The participants wore their usual running shoes to minimize discomfort or the introduction of changes in running style during the race.

Plantar pressure measurements were performed prior to the start of the race and approximately after one, two, three, four, and then every two hours during the race and immediately after the race.

In accordance with the duration of one lap run, every participant was requested one lap before the desired stopping point for the next measurement.

In accordance with Vallejo et al. (2011), participants stood in an upright position on the plantar pressure plate (Winpod Medicapteurs, Toulouse, France), with a shoulder-width separation between their feet and simulated gait by walking in place to accommodate the feet to the platform at the normal angle. After 15 seconds or so, they were told to stop moving and to stand still in a natural manner. After standing barefoot on the plate, recording started for 30 seconds. Participants using different lacing quick lock systems, data acquisition span lasted around one minute.

The plantar pressure data were normalized for foot length (Deschamps et al., 2015; Keijsers, Stolwijk, Nienhuis, & Duysens, 2009). For every pressure measurement record, to avoid influence of the projection of the centre of mass, subdivision between forefoot and rearfoot were determined from the length between the most ahead part of foot in pressure on ground and the most behind part of the foot in pressure on ground. From this longitudinal dimension, the foot was divided in forefoot and rearfoot in accordance with Burns et al. (2005) and Priego Quesada et al. (2015). The ratio between the mean forefoot pressure and the mean rearfoot pressure was calculated.

All of the rest periods (i.e., no displacement in more than 15 minutes and presence in the rest area) were recorded for each participant.

The time spent walking was calculated relative to the average distance run in one hour from the official data. The threshold was set in accordance with Hreljac et al. (2007) who indicated that the walk/run preferred transition speed in no inclination condition was around 1.9 $m.s^{-1}$ (i.e. 6.8 $km.h^{-1}$). To avoid any ambiguity, we have chosen 6 $km.h^{-1}$, that is, at the most, 10 minutes to run one lap. The experimentation place was near the time control. One investigator followed-up the participants' race as well as the real-time control sheet from the organizers.

The distance run at every measurement was calculated as the percentage of the total distance run. This percentage corresponds to the relative distance run.

The theoretical linear relative distance was calculated by reference to the total distance run. It corresponds to the proportional distance run per time unit relative to the total distance run.

The coefficient of variation of the distance run per time unit was calculated in accordance with the difference of the relative distance run relative to its value at the previous measurement.

For every participant, pressure measurements were the mean foot pressure, the value of the mean forefoot pressure and the mean rearfoot pressure, the ratio between the mean forefoot pressure and the mean rearfoot pressure, the mean normalized foot surface area, and the mean relative distance run and periods of rest and walking were determined from the follow-up the real-time control sheet of the organizers.

Statistical analysis

Means and standard deviations were calculated for all of the parameters for each participant. Repeated measures of ANOVA were used to determine significant differences between the intra-individual pressure and distance measurements. When a result of ANOVA showed statistical significance, the Bonferroni method was selected for multiple comparisons.

The Bravais-Pearson correlation coefficient was calculated for the correlation between the mean foot pressure, the ratio between mean forefoot and the mean rearfoot pressure and the relative distance, and between these same parameters and the elapsed time. From the correlation coefficient, the coefficient of determination was calculated.

The statistical significance level was set at $p < 0.05$ for all analyses. Statistical significance of correlations was defined at $p < 0.05$ and above $r^2 >$

0.28, significant threshold determined by the Bravais-Pearson statistical table (Fischer & Yates, 1975).

RESULTS

Preliminary processing of the data did not reveal any differences in terms of gender or between the dominant and the non-dominant foot. They were therefore all processed independently of gender and the dominant state.

Progression of the mean relative distance run

TABLE 1
Average and SD of the distance run and the participants' details prior to and after the race.

	Age (yrs)	Distance run (km)	Height (m)	Prior to the race		After the race	
				Weight (kg)	BMI (kg·m^{-2})	Weight (kg)	BMI (kg·m^{-2})
Mean	51.45	159.38	1.68	59.91	21.24	58.64	20.78
SD	7.93	32.95	0.11	8.07	1.29	8.12	1.35

On average, the participants ran 159.38 km (SD: 32.95) over the 24 hour period, which is slightly less than the length of four marathons (Table 1).

Figure 1a indicates that 25% of the total distance had been run by slightly after the third hour of the race (i.e., at 12.5% of the race duration), 50% of the total distance had been run by slightly before the 10th hour of the race (i.e., at 41.7% of the race duration), and 75% of the total distance had been run by approximately the 17th hour of the race (i.e., at 70.8% of the race duration). Statistical analysis between the theoretical linear relative distance and the progression of the mean relative distance run showed that, until the 12th hour of the race, the distance that was actually run was longer than the theoretical distance.

Although more than half the distance had been run during the first half of the race (i.e., 59.06% (SD: 2.55) in the first half *vs.* 40.94% (SD: 0.97) in the second half), studying the relative distance run between two time points does not allow the running strategy to be discerned, due to interindividual variability in particular (Figure 1b).

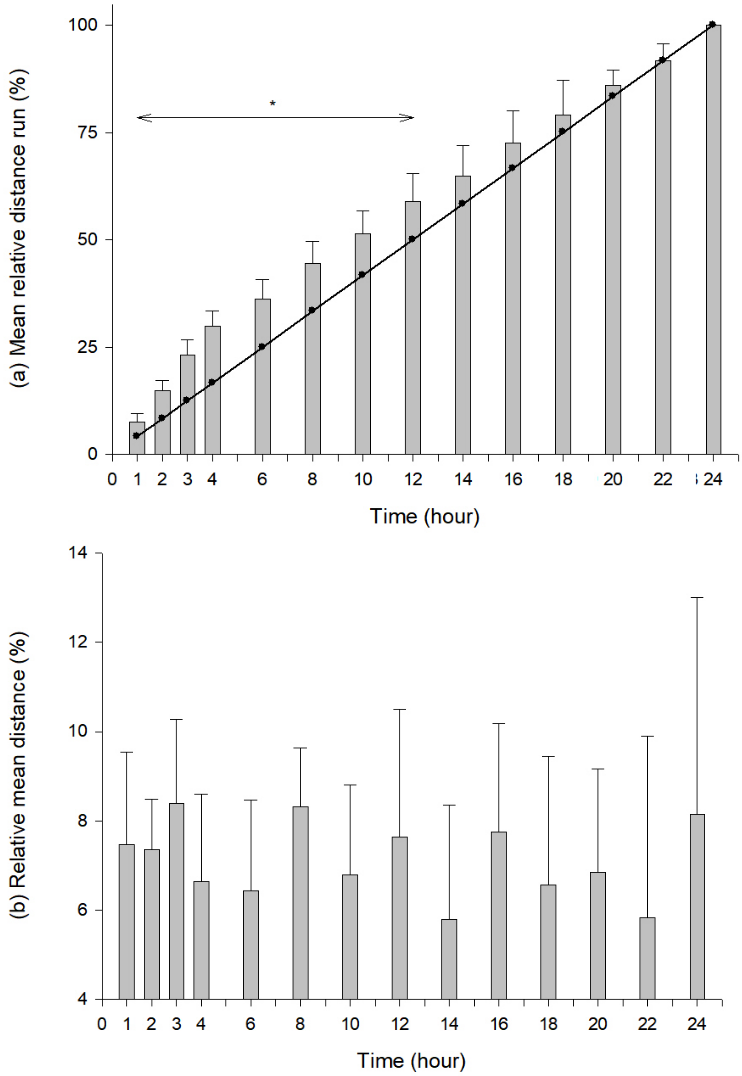

FIGURE 1: Mean and SD relative distances run over the course of the race relative to the linear theoretical distance (1a) and relative to the distance run and the SD between two data acquisitions. * indicates the period when distance that was actually run was significantly different from the theoretical distance.

Progression of the mean relative distance run

The statistical analysis revealed that the mean foot pressure decreased one-hour into the race ($p = 0.037$), between the 4th and the 6th hour of the race ($p = 0.045$), and between the last two hours of the race ($p = 0.011$). The mean foot mean pressure increased significantly between the 2nd and the 4th hour of the race ($p = 0.025$). There were significant changes between the start and immediately after the end of the race ($p = 0.010$).

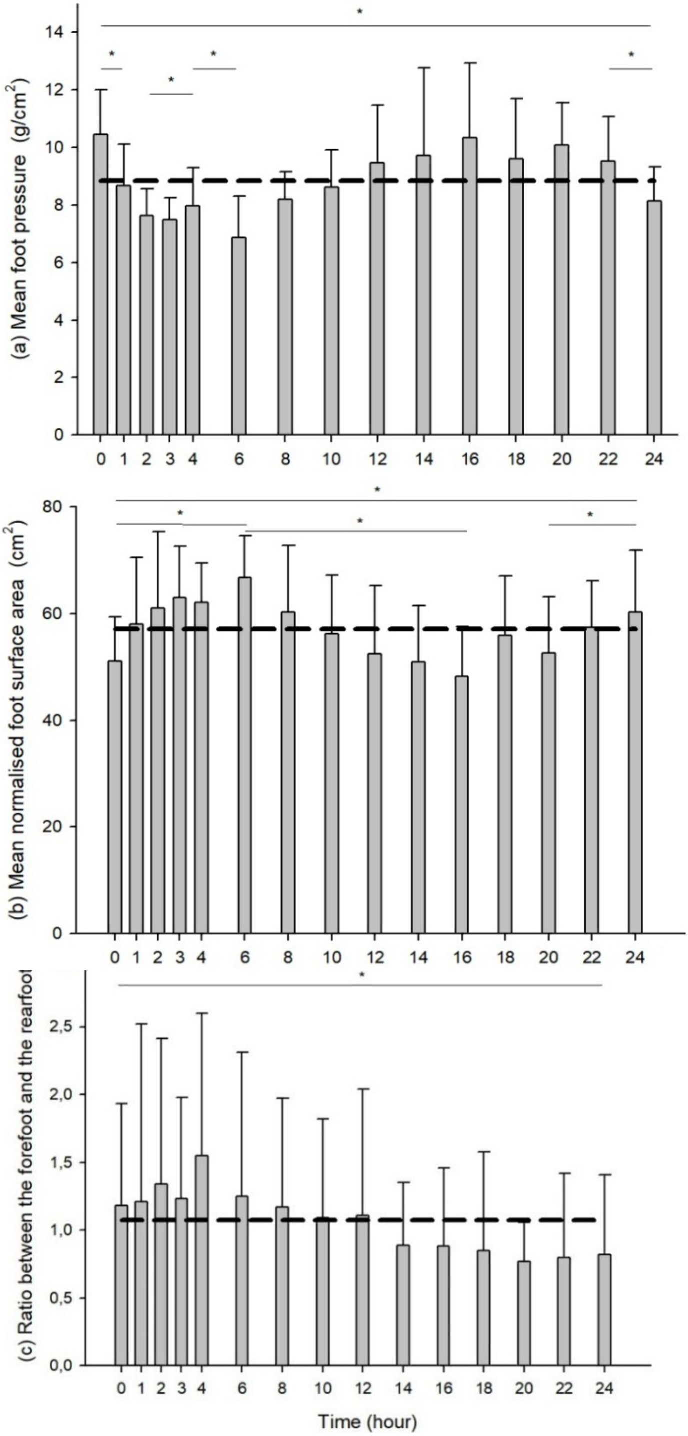

FIGURE 2: Mean foot pressure (2a), mean normalised foot surface area (2b) and the ratio between the forefoot and the rearfoot (2c) mean values and the SD over the course of the race. The dashed line indicates the average value. * indicates a significant difference between two measurements.

The mean foot pressure (Figure 2a)

The statistical analysis revealed that the mean foot pressure decreased one-hour into the race (p = 0.037), between the 4th and the 6th hour of the race (p = 0.045), and between the last two hours of the race (p = 0.011). The mean foot mean pressure increased significantly between the 2nd and the 4th hour of the race (p = 0.025). There were significant changes between the start and immediately after the end of the race (p = 0.010).

The mean normalised foot surface area (Figure 2b)

The mean normalised foot surface area increased significantly during the first 6 hours of the race. It decreased between the 6th hour and the 16th hour of the race (p = 0.003) after which it increased steadily until immediately after the race, with significant difference between the 20th hour and the end of the race (p = 0.004). The mean normalised foot surface area increased significantly between the start and immediately after the race (p = 0.024).

The ratio between the forefoot and the rearfoot (Figure 2c)

A value greater than 1 indicates that the pressure under the forefoot is higher than the pressure under the rearfoot. During the first half of the race, the pressure under the forefoot was higher than the pressure under the rearfoot. However, during the second half of the race, the ratio between the forefoot and the rearfoot was reversed, indicating that the pressure under the rearfoot increased. Thus, the ratio decreased significantly between the start and immediate after the end of the race (p = 0.041).

Correlation between the mean foot mean pressure and the relative distance run (Figure 3a)

The Bravais-Pearson correlation coefficient between the mean the foot pressure and the relative distance run did not indicate that there was a linear correlation (r^2 = 0.16).

Correlation between the mean normalised foot surface area and the relative distance run (Figure 3b)

The Bravais-Pearson correlation coefficient between the mean normalised foot surface area and the relative distance run did not indicate that there was a linear correlation (r^2 = 0.23).

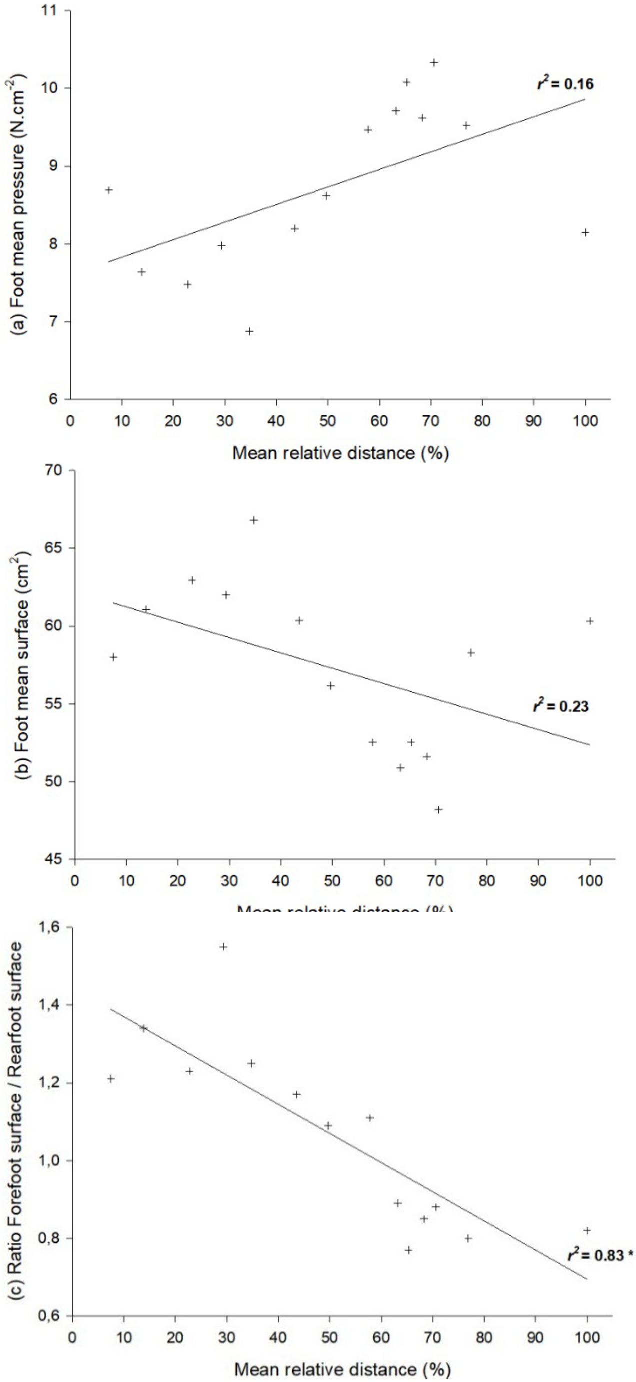

FIGURE 3: Correlation between the mean foot mean pressure (3a), the mean normalised foot surface area (3b), and the ratio between the forefoot and the rearfoot (3c) and the mean relative distance.
* indicates a significant correlation. *Correlation between the ratio between the forefoot and the rearfoot and the relative distance run (Figure 3c)*

The Bravais-Pearson correlation coefficient between the ratio between the forefoot and the rearfoot and the relative distance run indicated that there was a negative correlation (r^2 = 0.83); the greater the distance run, the lower the ratio between the forefoot and the rearfoot; that is to say, the pressure under the rearfoot increased.

Periods of rest and walking

Seven of the participants rested for an average of 3.57 hours (SD: 2.23) during the race independently of periods spent walking. Four of the participants walked for an average of 8.5 hours (SD: 6.02), without a rest period. Only one of the participants ran the entire race. This individual was also the one who ran the longest distance (221.56 km).

Periods of rest and walking primarily occurred after the middle of the race (73.7 % in the second half vs. 26.3 % first half; p = 0.01), of which 64.4% took place between the 12th and the 18th hour of the race and 35.5 % took place between the 18th and the 24th hour of the race (p = 0.01).

Periods of rest and walking primarily occurred about 3 hours after the usual sleeping hour according to the participant's declaration.

DISCUSSION

The aim of this study was to investigate progression of the plantar pressure over the course of a 24-h running race, particularly in regard to the time and the distance run.

Our results show that the runners adopted different running strategies, as indicated by the high level of interindividual variability relative to the distance run at each recording. Overall, the distance run was longer than the theoretical constant distance during the first half of the race. From mid-race to the end of the race, the significant decrease in the distance run appears to be due to an increase in periods of rest or walking and a decrease in the running speed. Interestingly, the coefficient of variation of the distance run per time unit is in accordance with that obtained by Lambert et al. (2004), who studied changes in running speeds during the first half of a 100 km race. Not surprisingly, due to the length of the race, interindividual variability of the distance run per time unit was higher until the 8th hour of the race. Aside from neuromuscular and physiological fatigue, this part of race occurred during the night, which was when runners had to manage the combined effects of pain, fatigue, and a sense of solitude (Simpson et al., 2014). These changes allowed for a degree of recovery, particularly in terms of plantar pressure (Kim, Mirjalili, & Fernandez, 2018).

During the first quarter of the race, which amounted to the distance of a marathon, the foot pressure decreased in keeping with an increase in the plantar surface area, and it was higher under the forefoot, which is in accordance with the findings of Hohman et al. (2016) for a race with a similar distance. Whereas the plantar surface decreased until the second third of the race, the mean pressure increased and moved to the forefoot. This result corroborates previous findings (Willems et al., 2012) and it may be explained by muscular pain of the plantar and dorsiflexor muscles (Hutson, 1984). Whether it was due to pain management or to taking a rest, this part of the race corresponded with an inversion of the forefoot pressure/rearfoot pressure ratio, which became less than 1. Novachek (1998) and Peltonen et al. (2012) indicated that at very slow running speed, the running pattern is modified with initial contact with a flat foot or by the heel. As proposed by Stolwijk et al. (2010), there was a decrease in roll-off, even when the participants ran very slowly, or they walked. During the last third of the race, the mean pressure increased, and its mean value was nearly the same as the value in the first third of the race.

Furthermore, according to Bus (2003) and Clarke et al. (1985), when fatigue occurs, the stride rate increases, and the stride length decreases to reduce the impact forces. Whether or not these changes increase knee flexion during ground contact according to Derrick (2004), Kim et al. (2018) and Mizrahi, et al. (2000) suggested that the mean angle of the knee is more extended as a result of the foot strike so as to resist the impact from loading as indicated by Arampatzis, et al. (1999). Moreover, Dierks et al. (2010) indicated that the knee internal rotation is also significantly increased, while the knee flexion at peak velocity is significantly decreased. According to Eslami et al. (2007), this knee internal rotation is associated with rearfoot eversion, which could increase the plantar surface area.

However, our results show that the plantar surface area decreased during the second third of the race, corresponding with an increase in the variability of the relative distance run and a reversal of the ratio between the forefoot and the rearfoot value from a value greater than 1 to a value of less than 1. The combination of two effects of fatigue in long distance running could explain the apparent contradiction. At the muscular level (i), foot-intrinsic muscle fatigue contributes to increased foot pronation (Headlee, Leonard, Hart, Ingersoll, & Hertel, 2008). This fatigue-related effect results in imbalance between the ankle flexor, such as the tibialis anterior (Segers, Lenoir, Aerts, & De Clercq, 2007), and extensor muscles; the activity of the latter increasing significantly in the fatigued state as compared to the non-fatigued state (Mizrahi, Verbitsky, Isakov, & Daily, 2000), and it exhibits a tendency toward an increased level of contraction of the antagonists (Gagnon, Bertrand Arsenault, Smyth, & Kemp, 1992). Thus, these changes in co-activation between agonist/antagonist muscles affect dynamic joint stiffness (Sanchis-Sales, Sancho-Bru, Roda-Sales, &

Pascual-Huerta, 2018). At the joint level (ii), imbalance between the ankle flexor and extensor muscles to the detriment of the latter induces a decrease of ankle plantar flexion and the subsequent subtalar joint pronation (Maharaj, Cresswell, & Lichtwark, 2017). As seen above, the knee is more extended as a result of fatigue in long distance running (Kim et al., 2018). The reversal of the ratio between the forefoot and the rearfoot pressure values during the second half of the race (from a value greater than 1 to a value of less than 1) indicates that the pressure increase under the rearfoot corroborates this assessment.

The decrease in muscle stiffness that generally occurs with fatigue (Sesboüé & Guincestre, 2006) tends to increase the plantar surface area value again during the last third of the race consecutive to knee and subtalar joints kinematics (Arampatzis, Brüggemann, & Metzler, 1999). Whereas the mean pressure during the second third of the race was higher than its mean value throughout the race, the increase in the plantar surface area induced a decrease in the mean pressure during the last third of race. Depending on the increase in the distance that was run during this part of the race, periods of rest and walking and/or a decrease of running speed at about mid-race could explain variations in the mean plantar pressure and the mean plantar surface area over the course of the race, However, the ratio between the forefoot and the rearfoot pressure values decreased significantly between the start and immediately after the end of the race. It appears that pressure is transferred preferentially to the rear-foot independently of rest and/or a decrease in the running speed around mid-race.

The analysis of the progression of the plantar surface area and the plantar pressure could be carried out through a coordinative approach. Millet (2011) has suggested that alteration of the running pattern could be a strategy to reduce the potential deleterious effects of ultra-long distance running, rather than decreasing the energy cost of running. In addition to a decrease in stride length and stride rate with a relative decrease of speed (Novacheck, 1998), changes in ankle and knee kinematics (Kim et al., 2018) induce a more *in-phase* coordination between the ankle and the knee, the ankle and the hip, and between the knee and the hip that is characteristic of non-expert runners (Dedieu & Zanone, 2013), or more specifically, of runners seeking to reduce lower limb pain consecutive to repetitive load impacts (Mizrahi et al., 2000).

Interestingly, the effects of a long-distance race appear to affect the plantar surface area and the foot plantar pressure independently of the distance itself. Instead, these depend on the duration of the race. The second third of the race appears to be crucial. Although fatigue occurs, monitoring of foot pressure indicates that many kinematic and muscular changes occur in a specific manner (Willems et al., 2012). While rest and/or a decrease in the running speed around mid-race tend to increase the mean value of plantar pressure, the transfer under the rearfoot and its consequence on the lower limb load charge remain unchanged.

Unlike in a single-marathon race, the monitoring of plantar pressure and plantar surface area over the course of a multi-marathon long-distance race indicated a non-linear progression of these parameters that are not in keeping with a type of deterioration. Although some of the observed results may contribute to the development of running injuries, our results could indicate a dynamical adaptation to protect against pain and the consequences of load impacts. The aim of this study was to investigate progression of the plantar pressure over the course of a 24-h running race. It was done during the French National 24-h championship. The observed results depend on the race conditions at the moment. To be generalized, it should be confirmed in different race conditions.

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