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The effects of fatigue on plantar pressure distribution in walking

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Abstract

The purpose of this study was to assess plantar pressure deviations due to fatigue. Plantar pressure was assessed using a portable system while eleven healthy subjects performed three walking tests, one before, one immediately after and another 30-min after intensive running. Pressure peak, intra-subject coefficient of variation and relative impulse were recorded. Significant decrease in pressure peak and the relative impulse under the heel and the midfoot along with significant increase in pressure peak and relative impulse under the forefoot were observed 30 min after the run. After a 30-min rest, the heel and forefoot loading remained significantly affected compared to the pre-test conditions while variability, step length and frequency remained unchanged. The study demonstrates short- and long-term plantar pressure deviations due to fatigue induced by an intensive 30-min run, while previous studies showed negligible deviation of the ground reaction force.

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Keywords: In-shoe measurements; Plantar pressure; Fatigue; Walking

1. Introduction

Previous studies on the effects of fatigue on ground reaction parameters have revealed negligible changes in ground reaction force [1,2]. Physiological studies, however, have revealed changes in muscle activation and contraction following short or long duration exercise. These concluded that fatigue induces changes in movement patterns [3]. The literature in this field is controversial and suggests that:

- (i) the physiological index of fatigue may not be sufficiently accounted for in studies focusing on mechanical parameters,
- (ii) the ground reaction force, may not be sufficiently sensitive to detect changes in foot contact, due to fatigue and

- (iii) exercise intensity and the characteristics of rest periods are ill defined in the literature. Therefore, it is not possible to clarify the effect of fatigue in previous studies.

The aim of this study was to determine the short- and long-term effects of fatigue induced by a 30-min running period set at 80% of the Maximal Aerobic Speed on plantar pressure distribution during walking.

2. Methods and procedure

2.1. Subjects

Eleven healthy male subjects (mean age: 23.9 ± 5.32 yr; mean height: 181 ± 6.2 cm; mean mass: 78.55 ± 5.76 kg) provided informed consent to participate in the study. A medical examination was undertaken to exclude subjects with foot or gait abnormalities. The subjects were students of the Faculty of Sports and Science, taking part on average seven times a week in sporting activities.

2.2. Protocol

The study was carried out over 2 weeks. During the first week the subject's maximal aerobic speed was determined using the

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Léger and Boucher test [4]. The University of Montréal Track Test took place on a 400-m track standardised with cones placed every 25 m. A pre-recorded soundtrack using brief sounds indicated the instant when the subject had to pass a cone in order to maintain a constant speed. A longer sound marked the changes in stage. The speed of the soundtrack was checked before every session. At the first stage, the speed was set at 8 km h^{-1} (2.22 m s^{-1}). It was increased by 1 km h^{-1} (0.27 m s^{-1}) every 2 min. The test was ended when the subject was no longer able to maintain the imposed running speed and the speed at the last completed stage was retained as the maximal aerobic speed.

During the following week, the session began with the determination of the subject's comfortable walking pace. During a series of familiarisation trials on the treadmill (MTC-1, Marquette electronic), the belt speed of the treadmill was progressively increased by 0.5 m s^{-1} until the subject confirmed their comfortable pace. The speed was then set, based on these walking tests performed on the treadmill. The subjects performed a walking test before (PRE-T), immediately after (POST-T) and 30 min after (POST30-T) the end of a running period. This period consisted of a 30-min run on a 400-m track with the speed set at 80% of the maximal aerobic speed. A pre-recorded soundtrack and cones placed on the track were used to impose the running speed. To control the intensity of the exercise, the heart rate and blood lactate were assessed before (PRE-T) and after (POST-T) the running period. Blood lactate samples were taken from the finger tip before and 5 min after the exercise. The Dr Lange, "miniphotomètre 8" portable system and a BHL 6000 sportester enabled blood sample analysis and maximal heart rate recording, respectively, during the 5 min following the end of the test.

2.3. Walking test protocol

Kinematic and kinetic parameters for walking have been reported to be "speed-sensitive" [5]. To ensure the same experimental conditions between the walking tests, the comfortable walking pace of each subject was determined just before the pre-test on the treadmill. It was then imposed during the POST-Test and POST30-Test.

In-shoe plantar pressure measurements were assessed using the Parotec system (Paromed Medizintechnik GMBH, Neubeuern, Germany), which consists of a right and a left insole (available in each shoe size) connected to an instrumentation module comprising a memory card located in a portable waist-mounted unit. The memory card allowed the recording of eight steps and the recordings were performed twice to reach 16 steps (eight left and eight right) per subject and per experimental condition. Each insole contained 16 fluid encapsulated "hydrocells" sensitive to normal and shear stress. The sampling frequency was set at 150 Hz. The subjects performed the running exercise wearing their own sports shoes. Since the plantar pressure is shoe-dependant, however, all subjects wore the same type of neoprene shoes to perform the walking test. This choice was dictated by the need for an insole without a plantar arch, in order to match the form of the Parotec insoles.

A three-step recording protocol is imposed by the Parotec system. During the first phase, the subject sat and kept his/her feet off the ground. The system recorded the pressures due to the shoe lacing. During the second phase, the plantar pressures were recorded in the standing position. The last phase corresponded to the dynamic plantar pressure recordings initiated with a remote control after 2 min walking to ensure the acclimatisation to the treadmill [5–8].

Several studies have already confirmed the validity and reliability of the in-shoe plantar pressure device [9]. Chesnin et al. [10] compared data recorded by the two systems (AMTI force-plate vs Parotec System). They provided good evidence for the accuracy and reliability of temporal measurements and peak force measurements taken with the in-shoe system. Therefore, the repeatability of the measurement values provided by the Parotec System was stable and consistent. The sensors were independently rated to perform with less than 2% measurement error across the expected pressure, temperature and humidity ranges of normal use [11]. Our own calibration confirmed these data. Hysteresis was 0.05% at 20 N/cm^2 , the temperature drift was $-0.015 \text{ N/cm}^2/\text{K}$ and humidity drift was negligible ($-0.001 \text{ N/cm}^2/\% \text{ humidity}$).

2.4. Parameters assessed

Blood lactate concentration is regarded as a good witness of acidosis and thus of the muscular fatigue induced by exercise [12]. Control of the exercise intensity enabled us to induce similar fatigue levels from one subject to another. Physiological indexes were maximal heart rate (HR) and blood lactate concentration [La]. They were measured before and after the 30-min running period.

The walking parameters consisting of walking velocity (V), step length (SL), step frequency (SF), double support time (DST) and contact time (CT) were measured. The Parotec system recorded step time (ST) as the time between two consecutive heel-strikes. Contact time (CT) was recorded between the heel-strike and the toe-off of the same foot. Double support time (DST) corresponded to the time when both feet were in contact with the ground. Step frequency (SF) was computed from the step time [i.e. $\text{SF} = 1/\text{ST}$]. Step length (SL) was computed from the velocity (V, imposed by the treadmill) and the SF [i.e. $\text{SL} = \text{V}/\text{SF}$].

The ground reaction parameters consisted of peak pressure (PP) and relative impulse (RI). Relative impulse was calculated by dividing the local impulse (force to time integral) by the total impulse calculated as the sum of all local impulses. Relative impulse allowed us to discard the body weight and foot size effects on plantar pressure distribution [14].

The Parotec system transducers were grouped to describe eight footprint locations, according to Milani and Hennig [13]. The rearfoot and the midfoot were defined by lateral heel (LH), medial heel (MH), lateral midfoot (LM) and medial midfoot (MM). The forefoot was divided into four footprint areas corresponding to the first metatarsal head (M1), the second and third metatarsal heads (M2-3), the fourth and fifth metatarsal heads (M4-5) and the Hallux (H). According to our previous investigations [14], peak pressure and relative impulse were computed for each footprint location as follows. Pressure due to shoe lacing recorded during the first phase of the walking test was discarded from the dynamic pressure before computation of plantar pressure parameters. This method ensures good reproducibility of the parameters when the shoes and the measurement insoles have to be removed and put back on. Our own tests demonstrated pressure peak coefficients of reliability from 0.88 to 0.99 according to the footprint areas when the measurements were performed before and after shoe and insole removals [14].

2.5. Statistical analysis

All statistical analyses were performed using Statistica 6.0. The Parotec memory card enabled to record eight steps during the

Table 1

Spatio-temporal parameters, during walking at 1.16 (0.02) m s⁻¹ before (PRE-T), immediately after (POST-T) and 30-min (POST30) after the exercise that induced fatigue ($n = 11$)

| | PRE-T, mean (S.D.) | POST-T, mean (S.D.) | POST30-T, mean (S.D.) |
|----------------------------|--------------------|---------------------|-----------------------|
| SL (m step ⁻¹) | 0.67 ± 0.05 | 0.65 ± 0.04 | 0.65 ± 0.04 |
| SF (step s ⁻¹) | 1.75 ± 0.13 | 1.78 ± 0.11 | 1.78 ± 0.13 |
| CT (s) | 0.70 ± 0.06 | 0.68 ± 0.06 | 0.68 ± 0.06 |
| DST (s) | 0.13 ± 0.03 | 0.12 ± 0.03 | 0.12 ± 0.02 |

Mean and standard deviation (S.D.); SL, step length; SF, step frequency; CT, contact time; DST, double support time. No statistically significant difference was observed due to fatigue ($P < 0.05$).

walking test that were performed twice. The intra-subject coefficient of variation (CoVi, i.e. S.D./mean) was calculated from the data of 16 steps (eight right and eight left) by the same subject. Left and right CoVi of the subject were then averaged.

Assuming that there is no significant side difference due to fatigue, the two side parameters were mixed and standard statistical methods were used to calculate means and standard deviation over the eight left and eight right consecutive steps. A Friedman ANOVA and a post hoc Wilcoxon ($P < 0.05$) matched pairs test were used to test the effect of the three conditions (PRE, POST and POST30-Test) [15,16].

3. Results

The maximal heart rate (HR) and blood lactate concentration [La] were 60.5 (±1.16) beats min⁻¹ and 2 (±0.03) mmol l⁻¹ before the exercise, respectively. HR and [La] increased significantly ($P < 0.05$) up to 126.18 (±0.65) beats min⁻¹ and 9.9 (±0.32) mmol l⁻¹ after the running period, respectively.

The spatio-temporal parameters are reported in Table 1. Step length (SL), step frequency (SF), contact time (CT) and double support time (DST) were not significantly affected by fatigue ($P < 0.05$).

The mean intra-subject coefficients of variation of the peak pressure are presented in Fig. 1 for each footprint location. No significant difference due to fatigue was noticed.

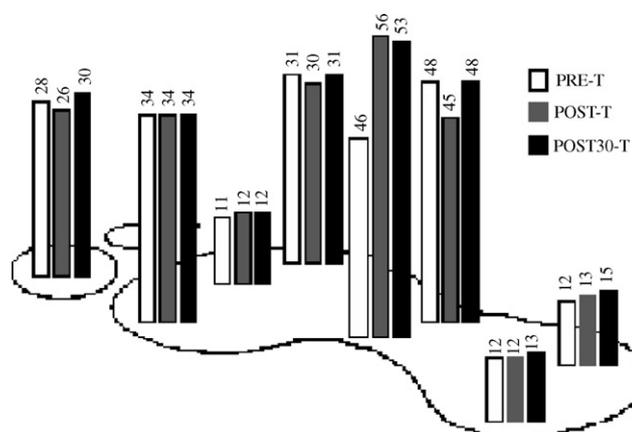


Fig. 1. Mean of intra-subject coefficient of variation (in %). No CoVi statistical difference was observed.

Table 2 presents the peak pressure (PP, in kPa) recorded under the eight footprint locations during the three walking tests. The PP under the medial heel decreased significantly ($P < 0.05$) by 8% between PRE-T and POST30-T. The PP under the medial midfoot decreased by 66% between PRE-T and POST-T and remained stable until POST30-T. Under the second and third metatarsal heads, the PP increased by 10% between PRE-T and POST-T and by 11% between PRE-T and POST30-T. The PP decreased significantly by 13% under the first metatarsal head between PRE-T and POST30-T. The PP decreased significantly ($P < 0.05$) by 12% under the Hallux between PRE-T and POST-T.

The relative impulses (RI, in %) of each footprint location are presented in Table 3. The RI increased significantly ($P < 0.05$) by 18% under the lateral heel between PRE-T and POST-T and by 17% between PRE-T and POST30-T. Under the second and third metatarsal heads, the RI increased significantly by 15% between PRE-T and POST-T and PRE-T and POST30-T. The RI of the Hallux decreased by 27% in POST-T but returned to the initial value in POST30-T.

4. Discussion

The effects of prolonged exercise, such as running or cross-country skiing, upon neuromuscular performance

Table 2

Mean of plantar pressure peak (in kPa), before (PRE-T), immediately after (POST-T) and 30-min (POST30) after the exercise that induced fatigue ($n = 11$)

| | PRE-T, mean (S.D.) | POST-T, mean (S.D.) | POST30-T, mean (S.D.) |
|--------|--------------------|---------------------|-----------------------|
| LH | 134 ± 24 | 133 ± 12 | 135 ± 29 |
| MH | 154 ± 15 | 141 ± 09 | 136 ± 12 [†] |
| LM | 27 ± 12 | 27 ± 13 | 24 ± 11 |
| MM | 3 ± 1 | 1 ± 0* | 1 ± 0 [†] |
| M1 | 165 ± 15 | 152 ± 19 | 144 ± 15 [†] |
| M2-3 | 190 ± 13 | 209 ± 24* | 210 ± 07 [†] |
| M4-5 | 137 ± 27 | 127 ± 25 | 125 ± 39 |
| Hallux | 129 ± 18 | 114 ± 11* | 115 ± 13 |

Mean and standard deviation (S.D.); LH, lateral heel; MH, medial heel; LM, lateral midfoot; MM, medial midfoot; M1, first metatarsal head; M2-3, second and third metatarsal heads; M4-5, fourth and fifth metatarsal heads.

* Differences statistically significant between PRE-T vs POST-T ($P < 0.05$).

[†] Differences statistically significant between PRE-T vs POST30-T ($P < 0.05$).

Table 3

Mean of relative impulse (in %), before (PRE-T), immediately after (POST-T) and 30-min (POST30-T) after the exercise that induced fatigue ($n = 11$)

| | PRE-T, mean (S.D.) | POST-T, mean (S.D.) | POST30-T, mean (S.D.) |
|--------|-----------------------|------------------------|--------------------------|
| LH | 10.9 ± 1.14 | 12.9 ± 1.48* | 12 ± 1.37 [†] |
| MH | 12.8 ± 1.31 | 13.4 ± 1.45 | 13.1 ± 1.44 |
| LM | 3 ± 1.57 | 3.4 ± 1.88 | 2.9 ± 1.39 |
| MM | 0.2 ± 0.09 | 0.2 ± 0.08 | 0.1 ± 0.08 |
| M1 | 19.8 ± 4.33 | 18.7 ± 4.73 | 18.3 ± 4.51 |
| M2-3 | 23.5 ± 2.69 | 27 ± 3.80* | 27 ± 3.93 [†] |
| M4-5 | 18.7 ± 3.73 | 17.7 ± 3.42 | 18.6 ± 3.54 |
| Hallux | 11.4 ± 2.66 | 8.4 ± 2* | 9.6 ± 2.90 |

Mean and standard deviation (S.D.); LH, lateral heel; MH, medial heel; LM, lateral midfoot; MM, medial midfoot; M1, first metatarsal head; M2-3, second and third metatarsal heads; M4-5, fourth and fifth metatarsal heads.

* Differences statistically significant between PRE-T vs POST-T ($P < 0.05$).

[†] Differences statistically significant between PRE-T vs POST30-T ($P < 0.05$).

have previously been investigated [3,17–19]. Indeed, Nicol et al. [3] showed that repeated stretch–shortening cycles during the running of a marathon affected force production by reducing neural input to the muscles and lowering the efficiency of the contractile mechanism. During intensive exercise, lactate does not exert any significant influence on the mechanical characteristics of the muscle [20,21] but affects the deterioration of the excitation process [22]. Physiological effects of fatigue on the excitation and efficiency of muscular mechanism, induce disturbance of the gait pattern.

Hausswirth et al. [23] showed that both stride length and frequency change at the end of a prolonged run. Mizrahi et al. [24] showed that stride rate in treadmill running at a given speed decreases with prolonged running fatigue. From a mechanical point of view, changes in the gait pattern necessarily induce changes in the ground reaction force.

Notwithstanding, Reinschmidt et al. [1] showed no significant difference in ground reaction force after a 30-min run, performed at the subjects' self-selected speed. Nevertheless, this study was limited to the vertical component (Fz) recorded by the force platform and the fatigue induced by the exercise was not quantified.

The aim of our study was to investigate the effect of a 30-min intense running period (80% of maximal aerobic speed) on kinematic and kinetic parameters of the gait pattern.

Our subjects presented mean blood lactate concentration (9.9 mmol l^{-1}) and maximal heart rate values ($126.18 \text{ beats min}^{-1}$) similar to those reported by Cazorla et al. [25] after the 30-min intense run. Exceeding the level of 8 mmol l^{-1} , the running exercise results in high blood lactate concentration that is supposed to disturb muscular excitation and efficiency and to induce modification of gait pattern. These results confirm the individualized running intensity (80% of maximal aerobic speed) of the exercise used to induce the fatigue.

Despite the intensity of the exercise, our results show no significant change in step length, step frequency, contact time and double support time. These parameters and the plantar peak pressure coefficients of variation were constant across the tests (Pre, POST-T and POST30-T). In previous studies the coefficients of variation of the peak pressure have been linked to the control of the re-equilibration process [13]. It seems that this process was not disturbed by fatigue in our study.

The spatio-temporal parameters and step-to-step intra-subject variability were stable across the tests. The differences in plantar pressure distribution, therefore, may be related to mechanical repercussions of movement pattern changes due to fatigue.

In fatigue conditions, reduced muscular control of the foot–shank joints may impair the ability to dynamically resist eversion or inversion [26]. Several studies cover the influence of eversion–inversion on shock wave attenuation at heel-strike [27,28]. Mizrahi et al. [29] and Voloshin et al. [30] indicated that fatigue reduces the ability of the musculoskeletal system to attenuate the shock waves at heel-strike. The influence of fatigue on muscular activity was expressed as a decrease of the mean power frequency of electromyography signals subsequent to a 3-h walking test [34] or high-intensity dynamic movement, such as running, cycling, or skiing [28,31–33]. In our study the plantar pressure peaks and the relative impulses recorded under the rearfoot (MH and LH) revealed changes with fatigue during the loading phase. Without other direct measures, we can only speculate that these observations may be linked to the eversion–inversion control, shock-wave at heel-strike and decrease in muscular power during the loading phase. It has become an accepted tenet of the practice of sports medicine that these parameters are responsible for a variety of symptoms in the lower extremities [35,36].

Plantar pressure peak under the midfoot (MM) significantly decreases with fatigue. Hennig et al. [13] postulate that these foot structures are involved in balance and movement control. From our results, it seems that these processes are disturbed by intense running. However, the study of the coefficient of variation did not confirm this idea and the disturbance of balance appeared to be a minor effect of fatigue. High standard deviation under these structures also revealed high inter-subject variation that could be linked to anatomical mid-arch differences. This point moderates the arguments on the effects of fatigue.

Under the forefoot, the short- (POST-T) and long-term (POST30-T) effects of fatigue induced plantar pressure peaks and relative impulse increases under M2-3, together with decreases under M1 and Hallux. Ferris et al. [37] found that regional contact areas, peak pressures and average pressures were significantly affected by simulated action of different muscular groups. Inactivity of the flexor hallucis longus muscle resulted in a decreased contact area of the big toe and a shift of loading to the forefoot. This result may explain the decrease in plantar pressure peaks and the

relative impulses of our study under the same footprint areas. Moreover, increased pressure under the head of the second metatarsal, causing increased force on the end of bone, resulted in an elevated bending moment. These large bending moments in the second metatarsal occurred when the toe flexors and the tibialis posterior muscle were inactive, thereby predisposing to a stress reaction [38]. In our study, the decrease in plantar pressure under M1 and the increase in plantar pressure peaks and relative impulse under M2-3 may be linked to a decrease in toe flexor and tibialis posterior activities due to fatigue. This finding may have clinical implications in the development of stress reactions or stress fractures.

This study used an individualized running speed set at 80% of the maximal aerobic speed to induce controlled fatigue. It has previously been shown that significant mechanical changes in the movement pattern induce deviations of the plantar pressure distribution. The effect of fatigue was observed immediately after and 30-min after the run. This study, therefore demonstrated the short- and long-term effects of fatigue when exercise intensity was individualized and controlled with physiological indexes such as blood lactate concentration and heart rate. The present study of plantar pressure measurements investigated for the first time the characteristics at the foot-to-ground contact changes due to fatigue. This study also revealed that plantar pressure measurements were sensitive enough to detect the effects of fatigue. Future investigation should be conducted to (i) clarify the effects of different exercise intensities, (ii) use plantar pressure measurement throughout exercise to detect the time and nature of the deviations linked to fatigue, which would help in injury prevention.

Conflict of interest

None.

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