

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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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 sportster 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/cm², 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

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