Effects of treadmill running and fatigue on impact acceleration in distance running

JOSE´ ANTONIO GARCI´A-PÉREZ1, PEDRO PE´REZ-SORIANO1, SALVADOR LLANA BELLOCH1, ÁNGEL GABRIEL LUCAS-CUEVAS1, & DANIEL SÁNCHEZ-ZURIAGA2

1Department of Sports and Physical Education, University of Valencia, C/Gasco´ Oliag, no 3, Valencia 46010, Spain, and 2Department of Anatomy and Human Embryology, University of Valencia, Valencia, Spain

(Received 25 July 2013; accepted 4 February 2014)

Abstract
The effects of treadmill running on impact acceleration were examined together with the interaction between running surface and runner's fatigue state. Twenty recreational runners (11 men and 9 women) ran overground and on a treadmill (at 4.0 m/s) before and after a fatigue protocol consisting of a 30-minute run at 85% of individual maximal aerobic speed. Impact accelerations were analysed using two lightweight capacitive uniaxial accelerometers. A two-way repeated-measure analysis of variance showed that, in the pre-fatigue condition, the treadmill running decreased head and tibial peak impact accelerations and impact rates (the rate of change of acceleration), but no significant difference was observed between the two surfaces in shock attenuation. There was no significant difference in acceleration parameters between the two surfaces in the post-fatigue condition. There was a significant interaction between surface (treadmill and overground) and fatigue state (pre-fatigue and post-fatigue). In particular, fatigue when running overground decreased impact acceleration severity, but it had no such effect when running on the treadmill. The effects of treadmill running and the interaction need to be taken into account when interpreting the results of studies that use a treadmill in their experimental protocols, and when prescribing physical exercise.

Keywords: Overground, accelerometer, shock attenuation, surface

Introduction
Overground running and treadmill running are two popular modes commonly employed in running research but the properties of different surfaces provoke biomechanical modifications in running gait (Garcia-Perez, Perez-Soriano, Llana, Martinez-Nova, & Sanchez-Zuriaga, 2013). Treadmills are often used in gyms, biomechanical studies, physical therapy practice, and rehabilitation medicine (Savelberg, Vorstenbosch, Kamman, van de Weijer, & Schambardt, 1998) because they provide several methodological advantages: higher...
repeatability of the trials, easier instrumentation, better control of the environment (temperature, humidity), speed, and slope, and less space required (Baur, Hirschmüller, Müller, Golldhofer, & Mayer, 2007; Lavcanska, Taylor, & Schache, 2005; Nigg, De Boer, & Fisher, 1995; Riley et al., 2008; Savelberg et al., 1998; Schache et al., 2001; Wank, Frick, & Schmidtbleicher, 1998). But the experimental evidence that the treadmill can modify the basic running pattern should be taken into account when interpreting the results of studies conducted on this surface (Savelberg et al., 1998). In particular, several important biomechanical variables may be affected by the treadmill, such as stride frequency (Reinisch et al., 1991; Riley et al., 2008; Schache et al., 2001; Wank et al., 1998), contact time (García-Pérez et al., 2013; McKenna & Riches, 2007; Schache et al., 2001; Wank et al., 1998), lower extremity joint kinematics in the sagittal plane (Riley et al., 2008; Schache et al., 2001; Wank et al., 1998), muscular activity (Baur et al., 2007; Wank et al., 1998), energy expenditure (Pugh, 1970), shock attenuation (Hines & Mercer, 2004), and plantar pressures (Baur et al., 2007; García-Pérez et al., 2013). Even though the existing literature indicates that different running surfaces may lead to biomechanically different running patterns, some authors still consider that treadmill running may be a representative expression of overground running (Riley et al., 2008; Schache et al., 2001).

The degree of familiarity with treadmill running (Lavcanska et al., 2005), intra-stride treadmill speed variations (Savelberg et al., 1998), air resistance (Pugh, 1970), and the search for stability on the treadmill are the factors most often cited as responsible for the differences between treadmill and overground running (Baur et al., 2007; Nigg et al., 1995; Wank et al., 1998). Although fatigue is a significant factor in that it affects biomechanical aspects of long-distance running by decreasing the angle of the foot with the running surface at initial contact (Christina, White, & Gilchrist, 2001), by increasing stride length (García-Pérez et al., 2013), by changing the plantar pressure distribution (García-Pérez et al., 2013; Willson & Kernozek, 1999), and by modifying reaction forces (Weist, Eils, & Rosenbaum, 2004; Willson & Kernozek, 1999) and accelerations (Derrick, Dereu, & McLean, 2002; Mizrahi, Verbitsky, & Isakov, 2001), only one study has taken this aspect into account when comparing treadmill and overground running (García-Pérez et al., 2013). In this sense, different running surfaces lead to different patterns of muscle activity with their specific neuromuscular control mechanisms (Baur et al., 2007) and perceived levels of exertion (Thompson & West, 1998). The running surface could thus affect runners differently both physically and psychologically, and cause them to adopt different strategies of adaptation to fatigue, even though the plantar pressure study cited above (García-Pérez et al., 2013) found no interaction between fatigue and running surface (treadmill vs overground).

A typical 30-minute run incurs about 5,000 foot-strikes (Mercer, Bates, Dufek, & Hreljac, 2003). When the heel contacts the ground, the rapid deceleration results in a shock wave that is transmitted throughout the skeletal system from the leg to the head (Derrick, 2004; Derrick et al., 1998; Hines & Mercer, 2004). The energy of this wave is absorbed by various elements, including the running shoes, running surface, muscle, bone, and other structural tissues (Derrick, Hamill, & Caldwell, 1998). This process of absorbing impact energy, thus reducing the magnitude of the shock wave between the foot and the head, is termed shock attenuation (Derrick et al., 1998; Mercer, Vance, Hreljac, & Hamill, 2002). Shock attenuation and the severity of the impact acceleration are two of the most important variables analysed in running research because of their hypothetical relationship with potential injury (Milner, Ferber, Pollard, Hamill, & Davis, 2006; Mizrahi, Verbitsky, & Isakov, 2000a; Mizrahi et al., 2001), running performance (Derrick et al., 1998, 2002; Mercer et al., 2003; Verbitsky, Mizrahi, Voloshin, Treiger, & Isakov, 1998), fatigue (Derrick
et al., 2002; Mercer et al., 2003; Mizrahi, Verbitsky, Isakov, & Daily, 2000; Verbitsky et al., 1998), comfort, and sports equipment (Ly, Alaoui, Erlicher, & Baly, 2010).

Although it is known that the use of treadmills has the potential to change the biomechanical running pattern, there is no information available on the effect that this running surface in interaction with fatigue may have on the impact experienced by the runner. The aim of the present study was therefore to analyse, under pre- and post-fatigue conditions, the effect of treadmill running on impact acceleration and shock attenuation. It was hypothesized that: (a) treadmill running would reduce the impact acceleration, i.e. the peak acceleration and impact rate (the rate of change of acceleration), and the shock attenuation relative to overground running; and (b) the effect of the treadmill running on acceleration would be affected by the runner’s fatigue state.

Methods

Participants and experimental protocol

Twenty healthy recreational runners participated in the study: 11 men and 9 women (age: 34 ± 8 years, height: 172 ± 8 cm, mass: 63.6 ± 8.0 kg). The participants were experienced runners (9.5 ± 6.0 years). At the time of the study, they were training 4.2 ± 1.0 days per week, with an average of 49.8 ± 17.8 km per week. Participants were informed about the experimental characteristics of the study, and they all provided their written informed consent. All experimental procedures followed the principles of the Declaration of Helsinki and were approved by the Ethical Committee of the University of Valencia.

Participants performed three running tests on different days. First, each participant underwent a maximal effort 5-minute run on a 400-m track (Berthon, Dabonneville, Fellmann, Bedu, & Chamoux, 1997; García-Pérez et al., 2013) in order to determine their individual maximal aerobic speed (4.61 ± 0.47 m/s). The second and third tests were overground (rubberized track) and treadmill (Excite Run 700, TechnogymSpA, Gambettola, Italy) runs (400 m at 4 m/s) performed in random order. On both surfaces, the participants warmed up freely for 15 minutes, which also allowed them to familiarize themselves with the treadmill (Lavcanska et al., 2005). Body accelerations were measured before and after a fatigue protocol consisting of a 30-minute run at 85% maximal aerobic speed (3.81 ± 0.40 m/s) using two lightweight capacitive uniaxial accelerometers (MMA7261QT, Freescale Semiconductor©, Munich, Germany; total mass: 55 g; dimension: 64 mm × 42 mm × 24 mm) attached firmly to the skin with double-sided adhesive tape. The accelerometers were secured by elastic belts around the proximal anteromedial aspects of the right tibia and around the forehead. Accelerations were logged for 10 seconds at 100 Hz, and the two accelerometers were synchronized using the SignalFrame software package (Sportmetrics©, Valencia, Spain).

The two runs measuring accelerations were carried out at similar times of the day under non-adverse climatic conditions. All participants used heel–toe running style and wore their own running shoes (the same for all three tests). The running speed in the 400-m track test was monitored and controlled by means of an acoustic signal system which marked the speed by means of cones placed around the track.

Acceleration measurements

From the recorded tibial and forehead acceleration signals (Figure 1), two parameters were determined relating to the moment of foot-strike: (a) peak impact acceleration, and (b) the
time between the minimum acceleration just before foot-strike and the peak impact acceleration. Peak impact acceleration was defined as the maximal amplitude of the accelerometer’s transient at foot-strike (Mizrahi et al., 2000a, 2001). Accelerations in the present work are expressed in units of standard gravity ($1 \text{ g} = 9.81 \text{ m/s}^2$). Additional variables calculated included impact rate (the rate of change of acceleration, measured as the ratio between the magnitude of the peak impact acceleration and the time taken for it to be reached) and the shock attenuation (the reduction in impact acceleration from the tibial to the forehead measurements, expressed as a percentage (Mercer et al., 2003)).

**Statistical analyses**

The mean values of three consecutive right stance phases were calculated for each variable and running condition (treadmill vs overground; pre-fatigue vs post-fatigue). Data were processed in the SPSS 18® statistics software package. After the variables had been checked for normality (Shapiro–Wilk test), they were subjected to a descriptive analysis and a two-way repeated-measures analysis of variance (ANOVA), considering fatigue (pre-fatigue and post-fatigue) and surface (treadmill and overground) as intra-subject factors. Mauchly’s test was applied to check the sphericity assumption of the repeated-measures ANOVA. When sphericity was satisfied, a one-way ANOVA was carried out. When it was violated, the most powerful correction among the following was applied to adjust the degrees of freedom: Greenhouse–Geisser, Huynh–Feldt, or lower-bound. In order to explore further the effects of the interaction between running surface and the runner’s fatigue state, post hoc paired $t$-tests with a Bonferroni adjustment for alpha inflation were carried out. An alpha level of 0.05 was then used for all the analysis but the Bonferroni-corrected post hoc test with an alpha of 0.0125.

The within-day reliability of the parameters recorded by the system for each running condition was determined using a repeated-measures ANOVA to calculate the intra-class correlation coefficient, ICC (2,1), according to the nomenclature proposed by Shrout and Fleiss (1979). Data for ICC calculations were obtained from the peak impact values of the three
consecutive right stance phases used for the calculation of all the variables. ICC values were between 0.72 and 0.85, indicating good reliability (Hopkins, 2000; Sleivert & Wenger, 1994).

Results

Statistical analyses showed a significant interaction \((p < 0.05)\) between the running surface and fatigue state factors for both the peak impact acceleration and the impact rate. In the pre-fatigue state, the tibial peak acceleration and impact rate experienced by the runner were significantly lower \((p < 0.05)\) on the treadmill than on the track. These differences between treadmill and track were not significant in the post-fatigue state (Table I). Furthermore, on the track, the tibial impact rate decreased \((p < 0.05)\) as a result of fatigue, whereas no such effect was observed on the treadmill (Table I). There were no significant differences between treadmill and overground running in terms of shock attenuation (from tibia to forehead). The forehead peak impact accelerations were significantly lower in the treadmill compared with the overground running, but only in pre-fatigue condition.

Discussion and implications

As in other studies (Mercer et al., 2002, 2003; Mizrahi, Verbitsky, & Isakov, 2000b), the observed acceleration patterns were characterized by a peak impact acceleration as a result of initial foot-strike for both treadmill and overground running. Only in the pre-fatigue condition did the treadmill pattern show significant reductions in peak impact accelerations and tibial impact rate relative to the overground case. These parameters have been studied for their potential link with the risk of injury (Milner et al., 2006; Mizrahi et al., 2000a), running performance and fatigue (Derrick et al., 2002; Mercer et al., 2003), and comfort and sports equipment (Ly et al., 2010). The present results for the non-fatigued state suggest that data on these parameters taken from treadmill tests might not carry over to the overground context.

The altered environment of treadmill running may force the runner to make adjustments in gait to maintain performance or to reduce the risk of injury (Derrick, 2004), and thus modify the accelerations they experience. The lower peak impact acceleration and impact rate observed in the treadmill case may in part be a consequence of greater effective mass at foot-strike (McKenna & Riches, 2007; Reinisch et al., 1991), which in itself would not necessarily imply lesser ground reaction forces (Derrick, 2004; Derrick et al., 2002). Peak pressure and reaction force are strongly correlated, however, and treadmill running has lower

<table>
<thead>
<tr>
<th>Pre-fatigue</th>
<th>Post-fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overground</td>
</tr>
<tr>
<td>Tibia peak impact acceleration (g)</td>
<td>24.6 ± 10.8</td>
</tr>
<tr>
<td>Tibia impact rate (g/s)</td>
<td>614 ± 245</td>
</tr>
<tr>
<td>Head peak impact acceleration (g)</td>
<td>3.2 ± 0.7</td>
</tr>
<tr>
<td>Head impact rate (g/s)</td>
<td>41 ± 10</td>
</tr>
<tr>
<td>Shock attenuation (%)</td>
<td>82.1 ± 9.7</td>
</tr>
</tbody>
</table>

Note: ‘g’ is the gravitational acceleration.
*Significantly different from the matching overground condition \((p < 0.05)\).
†Significantly different from the matching pre-fatigue condition \((p < 0.05)\).
peak pressures than overground running (Baur et al., 2007; Garcia-Pérez et al., 2013). One infers, therefore, that the lower pre-fatigue accelerations recorded in the treadmill case were not only due to such a difference in the effective mass, but also to lower reaction forces. Indeed, the effect in this sense would be double because not only is the runner able to maintain treadmill speed with less propulsive phase than when running overground (Baur et al., 2007; Reinisch et al., 1991; Savelberg et al., 1998), but the braking phase of the running gait would also be reduced so as not to move backwards and forwards on the moving belt.

An accelerometry variable that may reflect the impact severity more accurately when the effective mass is not constant is shock attenuation (Derrick, 2004), as how much need there is for attenuation may modify the runner’s kinematics and performance (Derrick, 2004; Derrick et al., 1998, 2002; Mercer et al., 2003). Any reduction in attenuation could increase the risk of spinal injuries and joint and cartilage degeneration (Mizrahi, et al., 2001; Mizrahi, Verbitsky, Isakov, & Daily). Hines and Mercer (2004) showed that there is reduced shock attenuation in treadmill running which could in part explain the observed kinematic differences between the two surfaces (McKenna & Riches, 2007; Reinisch et al., 1991) and the greater energy demand in overground running (Frishberg, 1983; Pugh, 1970; van Ingen Schenau, 1980). Indeed, this latter effect is too large to be due solely to the lack of wind resistance on the treadmill (Frishberg, 1983), but must involve other factors such as differences between the two surfaces in kinematics (van Ingen Schenau, 1980) or muscle coordination (Savelberg et al., 1998). Contrary to our expectations, however, the reduction in shock attenuation in treadmill running was not statistically significant. Because the acceleration reaching the head was lower in the treadmill case, the aforementioned hypothetical lower attenuation in treadmill running may simply reflect the reduced acceleration at the tibia (Derrick, 2004; Derrick et al., 1998, 2002; Mercer et al., 2002).

With respect to fatigue, the only difference found was that tibia impact rate was lower post-fatigue than pre-fatigue in the overground case. Fatigue led to no differences in peak impact acceleration or shock attenuation. While these findings are consistent with those of Mercer et al. (2003) and Abt et al. (2011) who also found no change in tibia acceleration, other workers (Derrick et al., 2002; Mizrahi et al., 2001) describe fatigue as increasing tibia acceleration. Fatigue was not found to cause any significant difference in shock attenuation. The literature was already apparently in conflict in this regard. While Mercer et al. (2003) reported a 12% decrease due to fatigue, Derrick et al. (2002) report an increase. As noted by Mercer et al. (2003), these apparent contradictions may have been the result of different studies using different methods such as running surface, sample of runners, and fatigue and measurement protocols. While it may be difficult to measure, control, and fully describe all these variables, especially when they are not the main objective of the study, they should be taken into account in interpreting results, replicating a study, or comparing results from different studies.

Mizrahi, Verbitsky, Isakov, & Daily (2000) report increased impact rate as a result of fatigue in a treadmill study, and the present findings for the treadmill case are not inconsistent with those. They would be completely contradictory, however, if one were only to consider the overground data for which fatigue led to a decrease in tibial impact rate (Table I). Derrick et al. (2002), in a treadmill study, found that fatigue increases tibial peak impact acceleration. Whereas this is not inconsistent with the results of the present study (Table I), we found there to be a significant interaction between the running surface and the fatigue state. This latter relationship had not been studied before and shows that the effect of fatigue on the tibial acceleration and impact rate could be conditioned by the running surface (treadmill vs overground).
Overall, the present finding that the accelerometry parameters of treadmill running are different from those of overground running in a pre-fatigue condition means that the choice and control of the running surface has to be a fundamental methodological issue in research design. This is especially important in that we found the surface chosen (treadmill or overground) to have an interaction with another important factor in running—the runner’s fatigue state. Given the lack of concordance found in the literature, in future research it would be interesting to study the characteristics of these adaptations and the thresholds of fatigue at which they occur (Abt et al., 2011; Mercer et al., 2003), and whether other variables besides fatigue, such as the runner’s experience and technical level, might have an interaction with running surface.

A limitation of the present study is that the accelerations were not measured at different times during the fatigue protocol. Another limitation is the low sampling frequency of the accelerometers (100 Hz), even though this kind of accelerometer has been used in a previous study (Lucas-Cuevas et al., 2013). Nevertheless, the within-day reliability of the peak impact values for each condition of surface and fatigue state was good, indicative of good reproducibility of the accelerometry results.

Conclusion

Running on a treadmill compared with running overground was found to significantly modify the peak impact acceleration and impact rate in a non-fatigued condition. The effect of the treadmill on the accelerations depended on the runner’s fatigue state, and the effect of the runner’s fatigue state on the accelerations was also influenced by the running surface. Therefore, the relationship between running surface and fatigue state should be taken into account when interpreting the results of studies that use a treadmill in their experimental protocols and when prescribing physical exercise.

References


