The influence of running shoes cumulative usage on the ground reaction forces and plantar pressure responses

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Abstract

The prolonged use of a running shoe is thought to affect the efficiency of its impact attenuation properties. However, its effect over biomechanical variables has yet not been well understood. The aim of this study was to examine the influence of running shoe usage on ground reaction force and plantar pressure parameters. Three male runners received four running shoes each to use at their training sessions. The Gaitway System was used to register the vertical component of the ground reaction force, whereas the contact area and peak plantar pressure at different regions of the foot were assessed via the the F-scan System. Data collection occurred at baseline (when the shoes were new - New) and after 100, 200 and 300km of use. The first peak decreased significantly from New to 300km ($p \leq 0.01$) and the loading rate showed a significant decrease at 200km in relation to the New condition ($p \leq 0.01$). Total area increased significantly from New to 100km ($p \leq 0.01$) of use and maintained a similar value when compared with the other conditions. There was a continuous and significant decrease ($p \leq 0.01$) on forefoot peak pressure as the mileage increased from New to 300km. The hallux peak pressure values were significantly smaller ($p \leq 0.01$) at 300km when compared with the New condition. Considering that the first peak, loading rate and plantar peak pressure values did not increase and that the plantar total contact area increased, it can be concluded that the running shoe did not suffer consistent alterations in ground reaction force and in plantar pressure after 300km of use.

UNITERMS: Biomechanics; Footwear; Cumulative use.

Introduction

Many studies have investigated the influence of running shoes on motion pattern (CLARKE, FREDERICK & COOPER, 1983; LUETHI, DENOTH, KAELIN, STACOFF & STUESSI, 1987; NIGG, BAHLSEN, LUETHI & STOKES, 1987; WIEGERINCK, BOYD, YODER, ABBEY, NUNLEY & QUEE, 2009), but it is yet not clear when the running shoes loses its ability to reduce impact forces during running and therefore leading to the replacement of the running shoe by a new one.

There is evidence that long distance running lead to repeated compressions on the shoes structure that can cause ruptures on EVA air cells and damage the midsole's foam (VERDEJO & MILLS, 2004). Apparently, these damages reduce its capacity to damp the impact forces (COOK, KESTER & BRUNET, 1985; DIXON, 2008). The usage imposed by runners wearing the shoes resulted in a decrease in impact attenuation of 20% after 150 miles (241 km) and of 30% at the end of 500 miles (805 km) of running (COOK, KESTER & BRUNET, 1985). This reduction in impact attenuation was measured mechanically, but the reduction of cushioning in used running shoes seems to influence also some biomechanical variables. For instance, VERDEJO and MILLS (2004) observed significant increase of 100% in plantar peak pressures values on the heel region for one running shoe after 500 km of use.

Although it seems that the usage affects the cushioning efficiency of the running shoes, the effect of prolonged use over some biomechanical variables of the running shoes is not well understood yet. For example, in mileages of 400 km of use, the biomechanical variables, impact forces and loading rates, did not show a systematic and significant increase that would lead to the conclusion that the impact loading properties of the running shoes have become worse (SERRÃO, SÁ & AMADIO, 2000). HAMILL and BATES (1988) observed small or no changes in ground reaction force parameters after 420 km of use. In both studies, despite the deterioration observed on materials used on the running shoes, the external forces remained similar between each other, suggesting that the runners may have applied an adaptation strategy to the situation imposed. KONG, CANDELARIA and SMITH (2008) observed an evidence of this adaptation by observing changes on the running pattern as a consequence of time of use of shoes, especially on ankle motion.

While some evidence suggest that usage do not influence the impact forces (HAMILL & BATES, 1988 SERRÃO, SÁ & AMADIO, 2000), one study suggest that the deterioration of the running shoe materials may cause an increase in plantar peak pressure (VERDEJO & MILLS, 2004), but only on heel region and for one subject. Therefore, more investigation is needed to understand how usage affects the running shoes responses. There is not enough evidence to understand the behavior of plantar pressure distribution over the different regions of the foot with increasing mileages of use.

The aim of this study is to investigate ground reaction force and plantar pressure distribution parameters in running shoes submitted to increased mileages of use. Considering the reviewed literature, it was hypothesized that the impact forces of the running shoes would not be affected and that peak plantar pressure values will increase with higher mileages of use.

Methods

Sample

Three male ultra marathon runners took part on this study (32 ± 7 years, 1.68 ± 0.07 m and 63.43 ± 1.44 kg). They were all rearfoot strikers and were used to running in treadmill. The participants were training over 200 km per week and were not involved in specific training for some race at the time of the study. Runners with high training volume were searched because it was intended to avoid long term deterioration on shoe materials. The participants gave informed consent to participate on this project and the experimental procedure was approved by the local Committee of Ethics in Research (protocol number 65, approved on 27/08/2004).

The focus of the study was on the interaction of runner and shoe and not on the responses of runner itself. Therefore, the number of tested running shoes should be enough (12 pair of shoes) to have an evidence on the influence of increasing mileages of use on the interaction of runner and shoe. That is the reason why it is believed that limited number of subjects would not interfere in that analysis, although the extrapolation of the results to other circumstances might be diminished.

Running shoes

Each participant received the same four pair of shoes to use in their training sessions. The running shoe models were chosen in common agreement with the runners from the commercially available models at the time of the study. They were all training shoes of different brands and prices varying between 100 and 200 dollars. This criterion was used in choosing the running shoes because of the differences that each running shoe have on fitting. Although the running shoes were of different brands, they all had similar constructions. They were all made of similar dual density EVA midsoles, with some specific technological element applied that was characteristic of each brand.

Experimental procedure

A Gaitway System Instrumented Treadmill 9810S1x (Kistler Instrumented Corp.; Amherst, USA) was used to measure the vertical component of ground reaction force. The instrumented treadmill consists of two piezoelectric force platforms mounted in series at the base of a Trotter Treadmill model 685. The treadmill was specially designed to be stiffer at its base than the commercially available treadmills in order to interfere minimally at ground reaction force measurements. The plantar pressure distribution was recorded using an F-Scan System (Tekscan Inc.; South Boston, USA). This system consists of flexible insoles with 0.18mm thickness and having 960 resistive sensors with spatial resolution of 5 mm. These instrumented insoles were positioned in shoe over its insole to measure the forces distributed on the plantar surface of the foot during the stance phase of running.

Each runner performed a 20 minutes run on the treadmill to serve as warm up and familiarization time. At the first ten minutes the runners were allowed to choose the running velocity, after which for the next ten minutes the running speed was set at $14 km.h^{-1}$. The acquisition velocity was chosen using the runner's mean training velocity in their running sessions. At the end of 20 min, two trials of 12 s, at 1000 Hz, were recorded by the instrumented treadmill using 14km.h-1 as running velocity. After the ground reaction force acquisition, the instrumented insoles were prepared to collect pressure and contact area measurements. At $14 km h^{-1}$, three trials of 4.17 s, at 120 Hz of sampling frequency, were recorded with the instrumented insoles. In this system, because of the amount of information to be processed, the sampling rate could not be set higher. In attempt to ensure reliable pressure data, in compensation to the relative low frequency of acquisition, three trials were obtained from each condition of use tested, resulting in approximately 30 to 35 foot contacts. Because the insoles present considerable loss in its precision (Hsiao, Guan, & Weatherly, 2002; Verdejo & Mills, 2004; Woodburn & Helliwell, 1997), for each data collection a new par of insoles was used. The insoles were calibrated every session by the present weight of the subject, while standing in one foot.

The running shoes were analyzed when New and at every 100 km of use until 300 km. After the first data collection (New condition), the participants were asked to use the shoes normally during their training sessions. When the running mileage summed up 100 km, they were asked to return for a new data collection. The control of mileage was made by the participants with a spreadsheet. They were instructed to fill up the running session information and were asked not to use the shoe again until the new measurement was made. Therefore, at the end of the process each running shoe had four usage conditions (New, 100 km, 200 km and 300 km of use). From the spreadsheet it was observed that all shoes were used exclusively on asphalt as it was asked previously to insure a similar condition of use to all shoes.

Data analyses

The ground reaction force was treated with a Matlab routine in Software Matlab 6.5 (The Mathworks Inc.; Natick, USA). This routine filtered the vertical component of ground reaction force with a low pass second order Butterworth filter, with cut off frequency of 140Hz. This cut off frequency was chosen because it presented the desirable noise reduction with low data exclusion. The stance phases were separated, the force was normalized by body weight and the three parameters used for analysis were obtained. From the instrumented treadmill consecutive ground reaction force curves were measured corresponding to the right and left stance phases during running, which were grouped together to compose the measurements for the given condition (n = 650). The data obtained from left and right stance phases were grouped because they did not present significant differences between them. From the vertical component of ground reaction force, first peak, time to first peak and loading rate parameters were obtained and used to characterize the shoes impact loading properties (FIGURE 1). The instrumented insoles were used to measure contact area and peak plantar pressure at different regions of the foot.

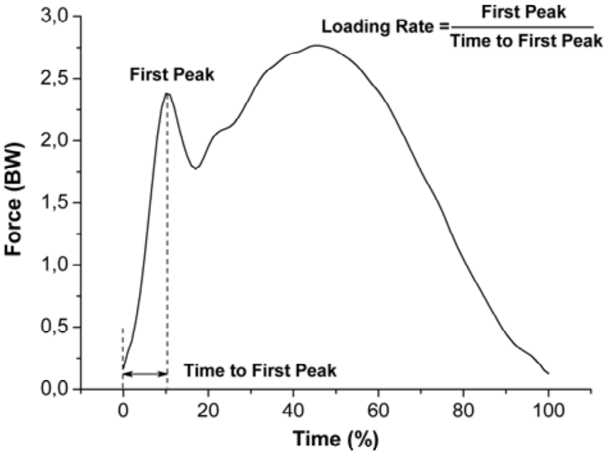

FIGURE 1 - Illustrative image of the vertical component of ground reaction force in which the first peak, time to first peak and loading rate can be observed.

The plantar pressure parameters were analyzed in Software F-Scan 4.10 (Tekscan Inc.; South Boston, USA). In this software the total plantar area was divided into the three areas of interest and from each plantar area the peak pressure and the area values were obtained. The plantar surface was divided into three areas: rearfoot (30%), midfoot (30%) and forefoot (40%) (See FIGURE 2), from which peak pressure and contact area values were obtained. The plantar pressure parameters were: total area, rearfoot area, midfoot area, forefoot area, rearfoot peak pressure, midfoot peak pressure, forefoot peak pressure and hallux peak pressure. The contact area measurements were used as a parameter that could suggest an accommodation in shoe materials and pressure measurements were used as an indicator of force concentrations on the foot structures. With the 12 running shoes and using the right and left stance phases together, approximately 396 stance phases were used to obtain the plantar pressure parameters.

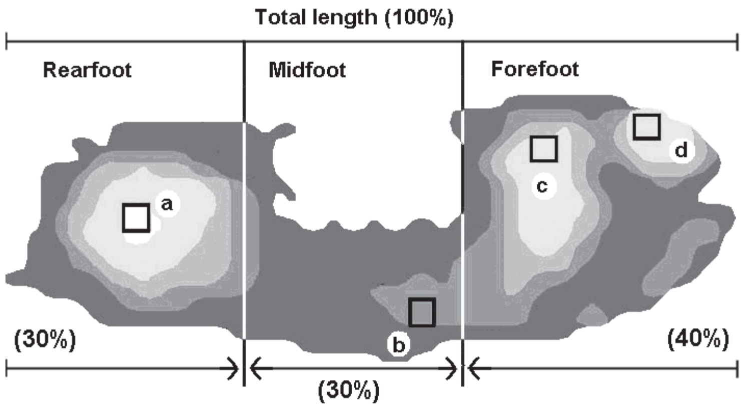

FIGURE 2 - Illustrative image of one stance phase obtained by F-scan System. The total length of the foot was divided in three regions: rearfoot (30%), midfoot (30%) and forefoot (40%). The boxes correspond to an example where the peak pressure values could be obtained in the rearfoot region (a), the midfoot region (b), the forefoot region (c) and the Hallux (d).

Data are presented as mean ± SD. Normality of the distribution was checked by the Shapiro-Wilk's test. One-way analysis of variance (ANOVA) with repeated measurements was run to test the effect of the mileage of use (four levels: New, 100 km, 200 km, 300 km) on ground reaction force and plantar pressure parameters. It was used TUKEY HSD test as post hoc. The statistical analysis was run in the Software Statistica V.5.1 (StatSoft Inc.; Tulsa, USA). The accepted p value for statistical significance was equal or less than 0.05 for all statistical analysis.

Results

The obtained parameters from ground reaction force were associated to the passive phase of the vertical force component: first peak, time to first peak and loading rate. The first peak showed a significant decrease ($p \leq 0.01$) from conditions New and 100 km to 200 km and 300 km. The time to first peak was significantly ($p \leq 0.01$) lower at 100 km and at 300 km than when the running shoes were New. At 200 km, the time to first peak showed similar values when compared to the condition New. The loading rate showed similar values at all mileages of use, except for 200km which showed significantly lower values ($p \leq 0.01$) than when the running shoes were New (See FIGURE 3).

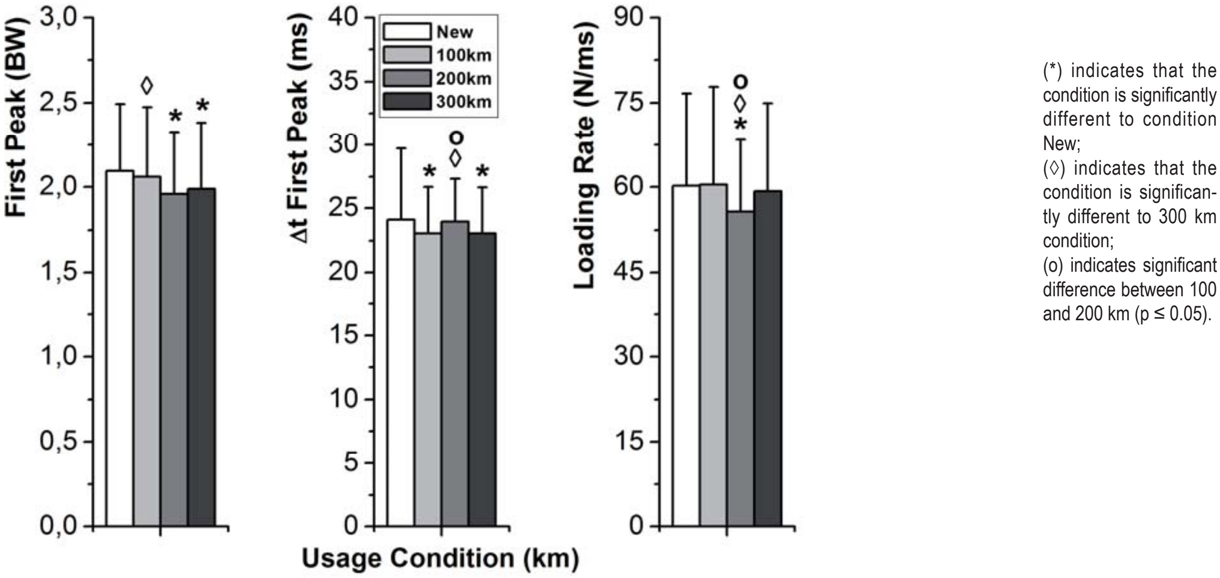

FIGURE 3 - First peak, time to first peak and loading rate values in the different usage conditions (New, 100, 200 and 300 km) for all running shoes.

Regarding the variables corresponding to plantar pressure distribution, the following results were observed (see FIGURE 4): the peak pressure values on the rearfoot were significantly smaller at 100 km ($p \leq 0.05$) compared with the condition New and 200 km ($p \leq 0.05$); the midfoot peak pressure values were significantly smaller at 100 km ($p \leq 0.01$) and 300 km ($p \leq 0.01$) compared with the condition New and at 200 km the midfoot peak pressure value was significantly greater than at 300 km ($p \leq 0.01$); the forefoot peak pressure values were significantly smaller at 100 km ($p \leq 0.01$), 200 km ($p \leq 0.01$) and 300 km ($p \leq 0.01$) compared with the condition New. At 100 km the forefoot peak pressure value was significantly greater than at 200 km ($p \leq 0.01$) and 300 km ($p \leq 0.01$); and the values of the hallux peak pressure were significantly smaller at 300 km ($p \leq 0.01$) than in the condition New.

The total contact area showed significantly lower values at condition New (188.73 ± 11.21 cm^2) than after 100 km (194.32 ± 9.81 cm^2, $p \leq 0.01$), 200 km (194.16 ± 9.79 cm^2, $p \leq 0.01$) and 300 km (193.77 ± 9.64 cm^2, $p \leq 0.01$) using the shoes. No other differences were observed in total contact area. The contact area at the rearfoot was significantly smaller at condition New than at 100 km ($p \leq 0.01$) and 200 km ($p \leq 0.01$) and at 300 km rearfoot contact area was significantly smaller than at 100 km of use ($p \leq 0.01$). At condition New, midfoot contact area values were significantly smaller than at 100 km ($p \leq 0.01$), 200 km ($p \leq 0.01$) and 300 km ($p \leq 0.01$) of use and at 100 km the area value was smaller than at 300 km ($p \leq 0.05$). Finally, forefoot contact area values were significantly smaller at New condition than at 100 km ($p \leq 0.01$) and 200 km ($p \leq 0.01$); and at 300 km the area values were also smaller than at 100 km ($p \leq 0.01$) and 200 km ($p \leq 0.05$) (FIGURE 4).

(*) indicates that the condition is significantly different to New condition;
(◊) indicates that the condition is significantly different to 300km condition;
(o) indicate significant difference between 100 and 200 km ($p \leq 0.05$).

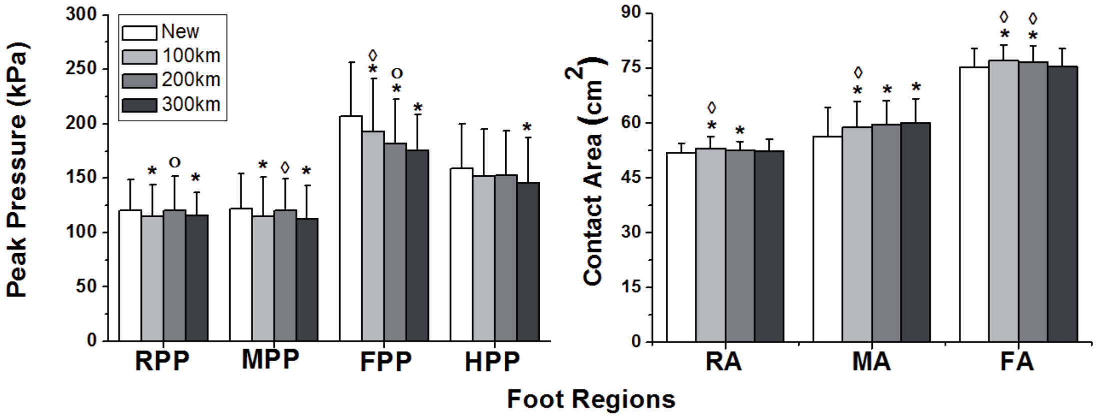

FIGURE 4 - Peak pressure values on the rearfoot (RPP), midfoot (MPP), forefoot (FPP) and hállux (HPP) and contact area values on the rearfoot (RA), midfoot (MA) and forefoot (FA) in the different usage conditions imposed (New, 100, 200 and 300 km).

Discussion

The aim of this study was to investigate how the kinetic responses of some running shoes would be affected by 300 km of use. The ground reaction force and the plantar pressure distribution variables were chosen for this analysis and based on the results it can be concluded that the running shoe did not become less effective in attenuating impact forces and plantar peak pressure after 300 km of use.

After 300 km of use, the ground reaction force first peak decreased significantly, the time to the first peak was significantly lower at 100 km and at 300 km, but similar values were found at 200 km and the loading rate was significantly lower at 200 km comparing with all other conditions. The running shoe is considered an important element for running because of its capability to control or reduce the impact forces (Clarke, Frederick & Cooper, 1983; Frederick, 1986; Nigg & Segesser, 1992; Richards, Magin & Callister, 2008). When this attenuation is not well adjusted, there is a risk of developing a chronic injury which is relevant because there is a high incidence of chronic injury in long distance running (Hreljac, 2004). The impact attenuation in running shoes is often investigated by analyzing the ground reaction force first peak, time to first peak and loading rate magnitudes (Davis, Ferber, Dieckers, Butler & Hamill, 2002; McPoil, 2000; Richards, Magin & Callister, 2008; Thacker, Gilchrist, Stroup & Dexter, 2002). Therefore, in theory, an increase in first peak and loading rate values and a decrease in time to first peak would suggest that the attenuation of impact loading is not being efficient. This was not the case because the results of this study do not suggest that impact attenuation was compromised by the mileages of use which is in agreement with the results obtained by Dixon (2008), Hamill and Bates (1988), Kong, Candelaria and Smith (2008) and Serrão, Sá and Amadio (2000).

Some studies indicated decreased impact loading properties after several mileages of use. Cook, Kester and Brunet (1985) using mechanical impact tests, observed a decrease of 20% in running shoes ability to attenuate impact forces after 150 miles (241 km) and a decrease of 30% after 500 miles (805 km) of use. In other study using a microscopy, Verdejo and Mills (2004) reported damages to the midsole that affected negatively the impact loading properties of the running shoe.

While impact tests (Cook, Kester & Brunet, 1985) and microscopical analysis (Verdejo & Mills, 2004) showed decrease in impact loading properties with usage, biomechanical analysis showed different results for impact loading. It is already known that mechanical test has low correlation with biomechanical tests (Clarke, Frederick & Cooper, 1983; Luethi et al., 1987; Nigg et al., 1987), because mechanical tests evaluate shoe's components characteristics; while biomechanical tests analyze the interaction between the running shoe and the runner.

Although, the shoes characteristics can affect the control on the external forces in running (Clarke, Frederick & Cooper, 1983; Kersting & Brüggermann, 2006; Luethi et al., 1987; Nigg et al., 1987), the efficiency to attenuate these forces in running depends on the interaction between the runner and its running shoe. For example, if the running shoes impact loading capability decreases for some reason, it could be possible to the runner to modify his running patterns in order to maintain external forces in acceptable ranges (KONG, CANDELARIA &SMITH, 2008).

Although mechanical tests were not performed in this study, some degeneration could be qualitatively observed in the components of the running shoes. Since the impact loading did not increased, these results suggest that the running shoes are still in conditions of use and if there was a compaction of the midsole, this would indicate that it probably became firmer. Thus, to keep the impact attenuation similar across mileages, the subjects possibly adapted their running pattern to the firmer midsole. Therefore, it can be speculated that the still adequate results of ground reaction force parameters after 300 km of use may be an indicator of some adjustment of the runner to the apparently degenerating running shoe. To confirm this speculation a study using more subjects would be needed to access the different adaptation strategies that different runners would apply.

The contact area shows how the foot is placed over the insole. Larger contact areas are desirable because they indicate that the foot is better accommodated over the insole and, therefore, it probably leads to lower peak pressures. The contact area showed some significant variation over the different mileages of use. Total contact area showed a consistent increase after 100 km of use that remained unchanged along the other conditions. Midfoot contact area showed a systematic increase in its values over the mileages of use ending in a significantly higher value at 300 km compared with when the shoe was new (FIGURE 4). Moreover, rearfoot and forefoot contact areas showed some variation along the mileages of use, but apparently with no clear tendency that could be considered a consequence of usage.

The responses suggest that there was an accommodation in shoe materials due to usage, which led to this change in the contact area. COOK, KESTER and BRUNET (1985) and HOUSE, WATERWORTH, ALLSOPP and DIXON (2002) suggest that the materials of the shoes, when under repeated compressive forces, suffer a certain amount of compaction that could lead to increased contact area. This speculation could be the explanation to the results seen in the present study, although to confirm this matter some structural analysis should have been conducted.

Many long distance runners believe that the running shoes should be softened before being used in their training sessions. The increase in total contact area may be a positive and desired modification that the shoes would present after certain time of use in running. It is not possible to precisely determine the amount of use that should be necessary to generate this possible accommodation, but these results suggest that it may occur on the first hundred kilometers of use.

On forefoot and hallux, the peak pressure values decreased as the mileages of use increased, leading to significant differences on peak pressure values at 300 km when compared to the condition New. In forefoot, the pressure values seem to show a trend of response that can be related to usage, because they were progressive over the mileages of use, meaning that they systematically increased at every condition. Furthermore, in rearfoot and midfoot, although pressure magnitudes did differ significantly, there was no consistent increasing in peak pressure values that could be associated to the mileages of use (FIGURE 4).

The variation observed in plantar peak pressure values seems to be different in rearfoot, midfoot and forefoot along the mileages of use. This distinct variation on the regions of the foot was also observed by DIXON (2008). It is possible that the regions of the shoe are compressed differently during the running cycle. Some regions may be more susceptible to usage than others and this characteristic can change from one running shoe to another. Since acquisitions frequency was very similar in the two studies, the cause for this different response on the shoe regions could be consequence of different materials used over the shoes length or maybe it is caused by the differences in midsole thickness throughout the shoe.

The peak pressure measurements of this study are not in agreement with the results obtained by VERDEJO and MILLS (2004). The authors analyzed the peak pressure values of the running shoe on the rearfoot area in one subject after 700 km of use and they observed that the peak pressure values increased consistently over the mileages of use. The differences in the results of the two studies could be consequence of the different experimental designs. It is possible that the different characteristics of the shoes used in both studies and/or the different conditions in which the running shoes were used for the training sessions caused the differences observed.

Variations in running technique, such as amount of pronation and other strategies, for example, could have interfered in the results of this study. The variability is natural and inherent to human locomotion and it can be observed between subjects and for the same individual in different days (WINTER, 1991). It is possible that this variability could have affected the effect of usage on the running shoe as well as the results obtained in different data collections, but it is believed that the interference in the results of study was not systematic.

The hypothesis of this study were that the impact forces of the running shoes would not be affected, but the peak plantar pressure values would increase with higher mileages of use. The hypothesis related to the impact forces was accepted but the hypothesis related the peak pressure value was refuted. Therefore it means that the kinetic responses of the running shoes were not affected negatively after 300 km of use.

Conclusions

Considering the present results, it can be concluded that there was no trend of increase in the external forces. Based on these results, the running shoes should be submitted to a period of use in which contact area would increase and possibly impact forces and peak pressure values would be maintained or attenuated. It would be wise not to use the new shoes for too long distances until it would be worn sufficiently. It is perhaps interesting to control the volume and intensity of training session at least while using a new running shoe. Through the mileages imposed, it is not possible to determine when the shoes would be worn out and would be up to replacement. Future studies should investigate the kinetic variables in running shoes submitted to higher mileages of use to try to determine when the shoes should be replaced.

Resumo

A influência do uso acumulado de calçados de corrida sobre a força de reação do solo e as respostas de pressão plantar

Acredita-se que a eficiência do calçado seja afetada pelo uso prolongado, mas as alterações biomecânicas ainda não estão bem compreendidas. O objetivo deste estudo é analisar a influência do uso de calçados de corrida na força de reação do solo e os parâmetros de pressão plantar. Três corredores do sexo masculino receberam quatro calçados de corrida para usarem em suas sessões de treinamento. O Sistema Gaitway e o Sistema de F-scan foram usados para registrar a força de reação do solo e parâmetros pressão plantar em diferentes regiões do pé. As coletas ocorreram em quatro momentos: novo e 100, 200 e 300 km de uso. O primeiro pico diminuiu da condição novo para os 300 km de uso ($p \leq 0{,}01$). A taxa de crescimento 1 diminuiu aos 200 km em relação às condições novas ($p \leq 0{,}01$). A área total aumentou aos 100 km ($p \leq 0{,}01$) de uso e manteve valores semelhantes e mais altos até 300km. No pico de pressão antepé, houve uma diminuição progressiva ($p \leq 0{,}01$) como o aumento quilometragem e os valores de pico de pressão do hálux foram significativamente menores ($p \leq 0{,}01$) aos 300 km do que na condição novo. Como o primeiro pico, a taxa de crecimento 1 e os picos de pressão plantar não aumentaram e a área de contato plantar total aumentou. Conclui-se que o calçado de corrida não sofreu alterações consistentes na força de reação do solo e na pressão plantar após 300 km de uso.

UNITERMOS: Biomecânica; Calçado; Uso cumulativo.

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