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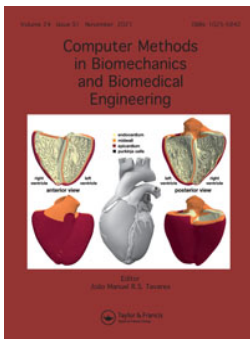
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Influence of midsole bending stiffness on impact loading of trail running shoes

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1. Introduction

The reduction of impact loading has been a matter of interest in the field of footwear design for decades. This is particularly relevant in the context of running, and especially trail running, where the repetition of ground impacts may alter neuromuscular function, promote the development of neuromuscular fatigue and ultimately, alter running performance. From a chronic perspective, the repetition of impacts may also contribute to the development of musculo-skeletal injuries. According to mechanical theories, improving shoe cushioning with increasing midsole thickness and the use of compliant and resilient materials may reduce impact loading. This has been the strategy employed in the design of ‘maximalist’ shoes. However, experimental evidence demonstrates that maximizing cushioning does not systematically translate into reduction of impact loading. Actually, some studies even demonstrated that softer midsoles increased impact loading (e.g. Kulmala et al. 2018). This is due to an adaptation of the running pattern, translating into an increased leg stiffness, especially at the level of the ankle joint, to preserve spring-like running mechanics (Kulmala et al. 2018) and improve stability when impacting soft materials/surfaces (Robbins and Waked 1997). Recently, the implementation of carbon plates in road running shoes allowed to improve energy cost (Hoogkamer et al. 2018) and running performances. Such innovation, which increases midsole bending stiffness, could improve foot stability and recoil of elastic energy at ground impact. This study aimed at verifying if this could translate into reduced impact loading of the lower limbs and therefore overcome the above-mentioned ‘cushioning paradox’.

2. Methods

2.1. Participants

Ten healthy male runners were involved after a medical examination (age: 31 ± 5 years old; height:

Table 1. Peak vertical acceleration and vertical loading rate measured at the heel with innovative (IS), standard (SS) and maximalist (MS) shoes (mean \pm SD).

Shoe	Peak (G)	Loading rate ($G \cdot s^{-1}$)
ISS	6.7 ± 1.2	806 ± 186
SS	6.4 ± 1.3	868 ± 249
MS	7.2 ± 1.2	786 ± 294

177 ± 6 cm; weight: 71 ± 7 kg). After being informed about the study, all participants gave a written consent to participate in this study. All participants were experienced, well-trained trail runners (experience >3 years of practice; training volume >5 hours per week) and free from muscular, bone or joint injuries.

2.2. Study design

The participants ran with three type of trail running shoes on a treadmill in a random order. Accelerometry was used to quantify impact loading and electromyographic activity (EMG) of the lower limb muscles was measured to identify any muscle tuning strategy.

The three tested shoes were 2 commercially available trail running shoes, used by top-level ultra-endurance runners, including a maximalist shoe (MS, Salomon S-Lab, stack: 20–28 mm, drop 6 mm), and a standard shoe (SS, The North Face Ultra-endurance 2, stack: 10–18 mm, drop 8 mm); and an innovative shoe, with a 0.6-mm full-length carbon plate embedded in the midsole (IS, The North Face Flight Vectiv, stack: 17–22 mm, drop 7 mm).

Two testing sessions, separated by 24 hours, were organized. During the first session, the participant performed a maximal incremental test to determine the velocity associated with maximal oxygen consumption (vVO_{2max}) during level running and a familiarization with the running tasks of the 2nd session. During the 2nd session, the participants performed 5 minutes of level running (slope +1%) running at 60% vVO_{2max} on a motorized treadmill with each of the three different type of shoes, in a random order.

Accelerometry and EMG data were collected during the last 2 minutes of each running task and averaged over this period, corresponding to 160 ± 15 steps.

2.3. Accelerometry

Tri-axial wireless accelerometers (G-Link[©]-200-OEM, LORD Sensing, Williston, VT, USA, mass 30g, sampling frequency 1024 Hz) were attached (1) to the right shoe heel, above the midsole, (2) to the antero-medial aspect of the right tibia, mid-way between the medial malleolus and medial epicondyle of femur, and (3) to the proximal median sacral crest. Peak

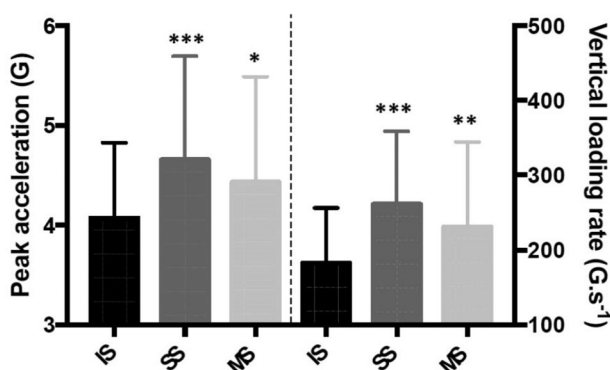


Figure 1. Peak vertical acceleration (left) and vertical loading rate (right) at the tibia during level running with innovative (IS), standard (SS) and maximalist (MS) shoes (mean \pm SD). Significantly different from IS: *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$.

vertical acceleration and vertical loading rate were computed from the collected data.

2.4. Electromyography

EMG activity of Vastus Lateralis, Tibialis anterior and Soleus was measured by wireless EMG sensors (Delsys Trigno[®], Boston, MA, USA). Data were sampled at a rate of 2 kHz within the 20–450 Hz bandwidth. Peak RMS values were quantified, averaged and expressed as a percentage of the maximal RMS, measured during a maximal voluntary contraction (*i.e.* knee extension, plantarflexion and dorsiflexion performed twice, for 5s, with a 90°-joint angle on an isokinetic ergometer).

2.5. Statistics

Normality of the data was checked with the Shapiro–Wilk test. A one-way analysis of variance and a Fisher post hoc test were used to test the differences between the different shoes. Significance level was set at $p < 0.05$.

3. Results and discussion

Participants ran at a speed of 10.0 ± 1.0 km/h. EMG activity did not differ between conditions. Acceleration data did not differ between conditions at the sacrum level and the heel level (Table 1). At the tibial level, both peak vertical acceleration and vertical loading rate were reduced with IS compared to MS and SS during level running (Figure 1).

4. Conclusions

Lower impact loading was observed at the tibial level with the shoe incorporating the carbon plate, confirming the starting hypothesis.

The fact that acceleration data did not differ at the sacrum level suggests that the impact dissipation at

the proximal level was similar between shoes. The observation that no difference was observed at the heel level, but at the tibial level, is consistent with the initial suggestion that adaptations of the running pattern, and specifically of the ankle joint stiffness, may modulate impact loading above the ankle level. The higher impact loading associated with the SS can be ascribed to its lower cushioning properties. Alternatively, the high impact loading associated to MS, despite its good cushioning, may result from the increased leg stiffness to preserve foot stability and recoil of elastic energy at ground impact (Kulmala et al. 2018). It is suggested that this effect was not observed with the IS because the inclusion of the carbon plate in the midsole improved passively the foot stability and recoil of elastic energy, avoiding any active compensation by the neuromuscular system.

This interpretation is limited by the fact that (i) foot strike pattern was not monitored in the current study and (ii) EMG activities did not differ between conditions. Nevertheless, we cannot rule out the possibility that EMG activities may have differed between conditions on muscles involved in foot and ankle stabilization (such as peronei muscles). Future research should evaluate if this reduced impact loading effectively translates into reduced neuromuscular fatigue and musculo-skeletal injuries to improve performance during prolonged trail running.

Disclosure statement

No potential conflict of interest was reported by the authors.

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KEYWORDS Accelerometry; impact; electromyography; stability; carbon plate

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