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Title: Textured insoles reduce vertical loading rate and increase subjective plantar sensation in overground running.

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Abstract

The effect of textured insoles on kinetics and kinematics of overground running was assessed. 16 male injury-free-recreational runners attended a single visit (age 23 ± 5 yrs; stature 1.78 ± 0.06 m; mass 72.6 ± 9.2 kg). Overground 15-m runs were completed in flat, canvas plimsolls both with and without textured insoles at self-selected velocity on an indoor track in an order that was balanced among participants. Average vertical loading rate and peak vertical force (F_{peak}) were captured by force platforms. Video footage was digitised for sagittal plane hip, knee and ankle angles at foot strike and mid stance. Velocity, stride rate and length and contact and flight time were determined. Subjectively-rated plantar sensation was recorded by visual scale. 95% confidence intervals estimated mean differences. Smallest-worthwhile change in loading rate was defined as standardised reduction of 0.54 from a previous comparison of injured versus non-injured runners. Loading rate decreased (-25 to -9.3 $BW \cdot s^{-1}$; 60% likely beneficial reduction) and plantar sensation was increased (46 to 58 mm) with the insole. F_{peak} (-0.1 to 0.14 BW) and velocity (-0.02 to 0.06 $m \cdot s^{-1}$) were similar. Stride length, flight and contact time were lower (-0.13 to -0.01 m; -0.02 to-0.01 s; -0.016 to -0.006 s) and stride rate was higher (0.01 to 0.07 $steps \cdot s^{-1}$) with insoles.

Textured insoles elicited an acute, meaningful decrease in vertical loading rate in short-distance, overground running and were associated with subjectively-increased plantar sensation. Reduced vertical loading rate could be explained by altered stride characteristics.

Key words: Biomechanics, Kinetics, Injury & Prevention

Introduction

Injury rates in running are reported between 19.4% and 92.4% annually, with stress fractures accounting for 20% of all injuries (van Gent et al., 2007). Meta analysis has shown vertical loading rate to differ (Cohen's d = 0.54) between runners suffering stress fractures and non-injured runners (Zadpoor & Nikooyan, 2011). It has been proposed as a causative factor in this type of injury, as well as injury to the knee (Davis, Bowser, & Hamill, 2010). This has led to investigations of footwear and gait manipulation that might reduce loading rate and potential injury risk (Giandolini, Arnal, et al., 2013; Warne et al., 2013). A recent meta analysis (van der Worp, Vrielink, & Bredeweg, 2016) confirms higher loading rate in runners reporting stress fracture injury compared with runners without injury, and a prospective 2-year follow up trial showed lower vertical loading rate in 'never injured' female runners compared to those that sought medical attention for injury (Davis, Bowser, & Mullineaux, 2016). Together this evidence provides a rationale for reducing vertical loading rate in running.

The plantar sensory feedback loop theory of Robbins *et al*. (1989) predicted that increased plantar discomfort from horizontal and vertical loading when barefoot would result in shock moderating, withdrawal reflexes in the legs that would reduce loading rate, plantar pressure and discomfort. This theory predicts that vertical loading rate will vary inversely with magnitude of plantar sensory feedback. A series of lab-based studies involving drop landings or controlled, vertical loading of the lower leg and foot on various surfaces designed to manipulate plantar sensory feedback, supported the theory (Robbins & Gouw, 1991; Robbins, Hanna, & Gouw, 1988). Moreover, a recent meta analysis suggests that added texture underfoot improves upright balance in young and healthy participants (Orth et al., 2013)

Application of the theory to locomotion was demonstrated by Nurse and Nigg (2001) and Eils *et al.* (2002). Nurse and Nigg (2001) used cooling to decrease sensation in different regions of the plantar surface and finally the entire plantar surface. Results showed alterations in peak plantar pressure between normal and reduced sensory conditions in walking. Specifically, areas of low sensation were avoided and pressure was increased in areas with normal sensation when cooling was localised. When the entire plantar surface was numb, peak pressure was increased compared to normal sensation. Authors suggested that increased peak pressure was an attempt to maximise feedback of location of bodyweight during stance (Nurse & Nigg, 2001). In contrast, anaesthetising the superficial plantar surface in a recent study did not affect changes in gait between barefoot and shod running suggesting deep rather than superficial sensory receptors are responsible for barefoot-gait adjustments (Thompson & Hoffman, 2017).

Increasing plantar sensation has also been shown to induce alterations in bipedal gait. Textured insoles were found to reduce loading rate compared to smooth insoles in walking (Nurse, Hullinger, Wakeling, Nigg, & Stefanyshyn, 2005). Chen *et al*. (1995) had previously demonstrated regional decreases in peak pressure and pressure-time integral in treadmill running with specially-designed socks containing coarse sand to increase plantar sensation, but vertical loading rate was not measured. With the exception of Chen *et al.* (1995) and Thompson & Hoffman (2017), previous studies have manipulated plantar sensory feedback during walking only.

Previous studies provide support for the efficacy of increasing plantar sensation to reduce vertical loading rate via altered gait characteristics. However, vertical loading rate has not been examined in overground running where plantar sensory feedback has been manipulated. The purpose of this study was to assess the effect of a textured insole, designed to increase plantar sensory feedback, on average vertical loading rate, spatiotemporal variables and kinematics in overground running. We hypothesised that textured insoles would increase subjective ratings of plantar sensation and reduce vertical loading rate.

Methods

Participants

With institutional-ethics approval, 16 male injury-free-recreational runners attended a single visit (age 23 ± 5 yrs; stature 1.78 ± 0.06 m; mass 72.6 ± 9.2 kg). Participants were recruited from staff and students in the department of Sport, Exercise and Rehabilitation at Northumbria University. Inclusion required participants to regularly run 3-10 km, 2-3 times weekly but not competitively. Volunteers were excluded if they had recent lower limb or foot injury affecting their running gait, were habitual barefoot runners, fore foot strikers, or had any contagious foot infection or any disorder affecting normal sensation of the plantar surface. Test-retest measurement error calculated from pilot test data of nine other runners was used to estimate sample size. Sample size was calculated to achieve sufficient precision of estimation to include a standardised-mean difference in loading rate between textured insoles and no insole conditions of 0.54 (previously shown to differentiate runners with and without stress fractures) (Zadpoor & Nikooyan, 2011), and to exclude a zero effect. Test-retest error for vertical loading rate was small (typical error 15 $BW\cdot s^{-1}$; 5.6%).

Design

After habituation to achieve a consistent self-selected endurance running velocity, participants completed overground, uni-directional 15-m runs on an indoor running track with walking recovery in flat-canvas plimsolls, both with and without textured insoles. Both conditions were performed without socks. Insoles were made from rubber and had a pattern of grooves and ridges aligned perpendicular to the long axis of the foot (Figure. 1a & b). Grooves were 1mm deep and the pattern had a pitch of 3mm. Total thickness of the insoles was 3mm. While the insole material was rigid enough that the texture did not deform under the weight of a person standing on it, the insole was very flexible, offering no additional restriction to foot flexion. The presentation of insole and no insole conditions was counterbalanced among participants to eliminate order effects. Both conditions were completed in a single visit. The canvas plimsolls were selected as the test shoe due to thin soles and absence of in-built cushioning.

Figure 1 about here

Procedures

Participants were provided with a tight fitting shirt and shorts to wear during trials. Reflective 25-mm markers were positioned over the right acromion process, greater trochanter (on the shirt and shorts respectively), directly on the lateral-femoral epicondyle and lateral malleolus, and on the plimsoll, directly over the posterior aspect of the calcaneus and distal-lateral aspect of the 5th metatarsal using double-sided-adhesive tape.

Ground reaction force was captured at 1000 Hz from two force platforms (OR6-7, AMTI, Watertown) embedded in series in one lane of the running track. Signals were filtered using a 2nd order Butterworth filter with a low-pass of 40 Hz and amplified (gain = 1000) and recorded in specialist software (Netforce 2.4.0, AMTI, Watertown).

Five 1-m sections of the modular Optojump system (Microgate, Bolzano-Bozen) were placed along the length of the lane, either side of the force plates to capture foot falls before, during and after force plate contact, enabling calculation of velocity, contact and fight time, stride length and stride rate. Video footage was captured by high-speed video camera (A602fc-2, Basler, Ahrensburg) operating through Motus 9 (Vicon, Oxford) and positioned on a tripod at a height of 0.7m and a distance of 4m from the centreline of the test lane. Capture rate of the camera was set at 100 frames/sec. A floodlight positioned behind the camera was used to increase marker contrast. The camera was calibrated using a 1-m square frame held in the centre of the test lane, perpendicular to the camera. The experimental set up is illustrated in Figure 2.

Figure 2 about here

Participants began running along the lane 10m before the force platforms, and were asked to continue to run through the Optojump tracks before decelerating. For habituation, participants were asked to perform as many practice runs as necessary without textured insoles, while velocity was monitored via the Optojump software until relative consistency (within 5%) was achieved. The participant was then informed data collection would commence. Five 'good' trials were recorded in each condition with 'good' defined as contact of the right foot completely on a force platform, without deliberate alteration of stride, at a velocity within 5% of that established during habituation. Immediately after completion of the five trials, participants were asked to mark on a 100mm visual-analogue scale to subjectively rate plantar sensation for the test condition. The scale ranged from "No sensation" to "Maximum sensation". They were then prepared for the next condition.

Data processing

Kinetic, kinematic and spatiotemporal variables were taken as the mean of the five 'good' attempts in each condition. Velocity, stride length, stride rate, contact and flight times were exported from the Optojump software into Excel for analysis. Force plate data were imported into BioAnalysis (Version 2.3, AMTI, Watertown), where they were normalised to standing body weight and percentage of gait cycle, before being exported into Excel to determine peak-vertical force (F_{peak}) and average vertical loading rate. Average vertical loading rate was quantified as change in force divided by time over the interval of 20-80% of the initial impact peak in vertical GRF in line with previous work (Williams, McClay, & Manal, 2000).

A spatial model was created in Vicon Motus consisting of six points, each representing one of the markers. Segments were created between these points representing the trunk, thigh, shank, foot and the floor. Software was set up to measure the hip angle (angle between trunk and thigh), knee angle, ankle angle and the foot-strike angle (angle between the foot and the floor). Foot-strike angle at initial contact was used to distinguish foot-strike pattern, where a positive angle indicates a rear-foot contact and a negative angle a forefoot contact (Lieberman et al., 2010). Centre of mass data were inserted for the body segments.

For each trial, the appropriate calibration and trial video clips were imported. Each marker was digitised, using automatic tracking, from initial foot contact to toe off. Marker coordinate data were filtered using a 4^{th} order Butterworth low pass filter set to 25 Hz. A virtual marker was created to represent the centre of mass and joint angles were calculated. All kinematic data were exported into Excel for analysis.

The video footage of the trial was examined to determine the frame at which foot contact was made on the force plate, and values for the hip, knee, ankle and foot angles were extracted for this frame. In addition, the X co-ordinates of the ankle marker and the centre of mass virtual point were examined for the point during stance when the centre of mass was vertically above the ankle. We named this centre of mass-ankle alignment (COM-A alignment). This frame was selected as a common point for comparison between conditions approximating the middle of the gait cycle. Joint angle data were also extracted for this frame.

Statistical analysis

After visual assessment and verification of underlying assumptions (uniformity of error and normality of difference scores), mean and SD were calculated for all variables in both conditions using Microsoft Excel. Subsequently, population-mean differences between conditions were estimated with 95% confidence intervals. For vertical-loading rate, in addition to the interval estimate, the probability of the population-mean difference between conditions exceeding a smallest-meaningful, standardised-mean difference of 0.54 was calculated using a magnitude-based inference approach (Batterham & Hopkins, 2006). This value is the estimated standardised-mean difference in vertical loading rate between runners with and without stress-fracture injury from meta analysis (Zadpoor & Nikooyan, 2011).

Results

Subjectively-rated plantar sensation

Plantar sensation was rated higher with the textured insole (78 ± 15 mm) than without (25 ± 13 mm) (95% CI for mean difference 46 to 58 mm).

Running velocity

Self-selected velocity was similar in the textured insole (4.21 ± 0.68 $m \cdot s^{-1}$) and no-insole (4.19 ± 0.66 $m \cdot s^{-1}$) conditions (95% CI for mean difference -0.02 to 0.06 $m \cdot s^{-1}$).

Kinetics

Average vertical loading rate was lower with textured insoles (111 ± 37 $BW \cdot s^{-1}$) than without (128 ± 37 $BW \cdot s^{-1}$). The mean reduction in average vertical loading rate was -17 $BW \cdot s^{-1}$ (15%) (95% CI -25 to -9.3 $BW \cdot s^{-1}$). Expressed as a standardised effect size, the reduction with textured insoles compared to without was 0.54 (95% CI 0.3 to 0.82). The probability of the population standardised-mean reduction exceeding the smallest-meaningful reduction of 0.54 was 60%. F_{peak} was similar between insole and no-insole conditions (2.80 ± 0.37 versus 2.77 ± 0.38 BW respectively; 95% CI of mean difference -0.1 to 0.14 BW). Individual differences in average vertical loading rate between the two conditions is illustrated in Figure 3. Figure 4 displays the average ground-reaction force traces for both conditions.

Figures 3 and 4 about here

Stride characteristics and kinematics

Stride length was reduced with (3.02 ± 0.36 m) compared to without (3.09 ± 0.37 m) the textured insoles (95% CI for mean difference -0.13 to -0.01 m). Flight time was shorter with (0.11 ± 0.02 s) than without (0.12 ± 0.02 s) the textured insoles (95% CI for mean difference -0.02 to -0.01 s) and stride rate was higher with (1.97 ± 0.14 steps·s^{-1}) than without (1.93 ± 0.17 steps·s^{-1}) the insoles (95% CI for mean difference 0.01 to 0.07 steps·s^{-1}). Contact time was lower with the textured insoles than without (95% CI -0.016 to -0.006 s). Foot-strike angle was similar with (12.9 ± 6.5°) and without (12.3 ± 7.1°) the textured insole (95% CI for mean difference -2.2 to 3.4°) indicative of all participants adopting a consistent rear-foot strike strategy in both conditions. There was a moderate correlation (r = 0.31) between change in stride length and change in vertical loading rate between the two conditions (95% CI for r 0.16 to 0.55). Sample means for each condition, mean differences and 95% CI for population mean differences between conditions in the remaining kinematic measures are shown in Table 1.

Table 1 about here.

Discussion

The purpose of this study was to assess the effects of a textured insole, designed to increase perceived plantar-sensory feedback, on average vertical loading rate, spatiotemporal variables and kinematics in overground running. Key findings were an acute reduction of average vertical loading rate, and an acute increase in subjectively-rated plantar sensation with textured insoles compared to without. This was accompanied by a reduction in stride length, flight and contact time and an increase in stride rate with the textured insoles.

Textured insoles elicited an acute and meaningful reduction of average vertical loading rate of a magnitude similar to the difference in loading rate between runners with and without stress-fracture injury (Zadpoor & Nikooyan, 2011). They were also associated with an acute increase in subjectively-rated plantar sensation. The decreased loading rate was unlikely to be an artefact of differences in running velocity, given that mean velocity was almost identical in both conditions. Moreover, observed reductions in stride length, flight and contact time, with concomitant increases in stride rate are gait adjustments that have been associated with a reduction in vertical loading rate in gait retraining studies (Giandolini, Arnal, et al., 2013; Samaan, Rainbow, & Davis, 2014). Some gait retraining studies have used real-time visual feedback as a cue to reduce vertical loading rate (Crowell & Davis, 2011; Samaan et al., 2014). These studies reduced vertical loading rate by 32% with eight sessions over a two-week period and by 57% in a single treadmill run of up to 10 minutes respectively. Vertical loading rate reduction in both studies was larger than observed here (11%). The duration and overt-visual nature of feedback in the previous studies might explain this difference. Given that no overt feedback about vertical loading rate was provided in either condition in the present study, it appears that elements of habitual-stride characteristics might be subconsciously adjusted in response to the perceived augmentation of plantar-sensory feedback. These adjustments appear to result in a reduction of loading rate without a change in velocity, in relatively few strides over a short distance. This explanation supports predictions of the plantar-sensory feedback theory (Robbins et al., 1989) that would suggest the adjustments in gait were made in response to the perceived increase in sensory feedback, with the goal of reducing the magnitude of the sensory signal in subsequent steps in a negative-feedback manner. Recent findings suggest that the gait alterations we observed are unlikely to result from stimulation of superficial plantar sensory receptors in the skin, but more likely from stimulation of deeper mechanoreceptor (Thompson & Hoffman, 2017). The rigidity of the ridges in our textured insoles and their arrangement perpendicular to long axis of the foot might be facilitate stimulation of deeper plantar-sensory receptors, but our design is unable to confirm this.

Despite alterations in stride length, stride rate, flight and contact time, no evidence was found to suggest changes in any other kinematic measure at initial contact or mid stance. It appears that simply reducing stride length is sufficient to reduce vertical loading rate. This suggestion is supported by our observed correlation between change in stride length and change in vertical loading rate. It is also supported by the findings of gait retraining studies in which stride rate (and thus stride length) were manipulated (Giandolini, Arnal, et al., 2013). Indeed, a recent study (Lieberman, Warrener, Wang, & Castillo, 2015) demonstrated a causal link between increased stride rate, reduced stride length and decreased vertical loading rate. The mechanical link between braking forces and accompanying high average vertical loading rates observed with longer stride length and lower stride frequency (Lieberman et al., 2015) could explain the findings presented here.

Notably, in this study participants achieved reduced loading rates between conditions but did not do this by changing foot strike patterns. Despite other studies showing lower vertical loading rates with a forefoot strike (Lieberman et al., 2010; Phan et al., 2016), and some actually instructing participants to consciously adopt this pattern (Giandolini, Horvais, Farges, Samozino, & Morin, 2013; Williams et al., 2000), all of our participants retained a rearfoot strike in both conditions. From an anatomical perspective, an elongated stride length resulting from an over stride at the knee strongly encourages a rear-foot strike (Lieberman et al., 2015). This landing strategy is most prevalent in runners wearing conventional-cushioned shoes and less prevalent in minimal footwear and barefoot runners (Larson, 2014; Lieberman et al., 2010). The footwear used in the present study were flat, flexible-canvas plimsolls that can be classed as minimal footwear. Despite this, all participants retained a rear-foot landing strategy in the test shoes that was consistent regardless of the insole condition. The short distances covered and short duration of wear might not promote a change in habitual-landing pattern and participants unaccustomed to running in minimal shoes might tolerate the short-term change.

The acute alteration of stride characteristics and associated reduction in loading rate in this study, suggests that textured insoles could be used as an aid to gait retraining. It is unlikely that a runner would tolerate the perceived increase in plantar sensation for the duration of a long run, but frequent short-term use might facilitate small adjustments in habitual-stride length, rate and contact time that could reduce long-term risk from loading-rate related injury. Clearly, these suggestions are speculative, but could be fruitful lines of future enquiry.

It should be noted that we did not quantify plantar sensitivity or individual sensitivity thresholds using methods such as Semmes-Weinstein monofilament testing. As such, ratings of plantar sensation and changes between conditions are subjective and not normalized to individual sensitivity thresholds. Accordingly, a causal link between textured insole use, the observed increase in subjectively-rated sensation, gait alteration and reduced vertical loading rate cannot be inferred.

The results of this study suggest that textured insoles produce meaningful, albeit acute, decreases in average vertical loading rate in short-distance, overground running. Increased subjectively-rated plantar sensation was also observed in the textured insole condition. Reduced vertical loading rate with the insole could be explained by altered stride characteristics in that condition. Future studies should examine the effects of longer durations of wear, explore the potential effectiveness of textured insoles as an aid to gait retraining and attempt to confirm a causal link between altered gait and plantar sensation using standard-objective measures of the latter.

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Table and figure headings.

Table 1. Joint angles at initial contact and at COM-A alignment in recreational runners (n = 16) during indoor-overground running at matched velocity in flat-canvas plimsolls both with and without textured insoles.

Figure 1. A canvas-plimsoll test shoe and custom-made textured insole with ridges at 3mm intervals and 1mm deep (a), and figurative cross-sectional view of the insole (b).

Figure 2. Schematic of the experimental set up.

Figure 3. Vertical loading rate of male recreational runners (n = 16) during overground, indoor running at matched velocity in canvas plimsolls both with and without textured insoles.

Figure 4. Average vertical ground-reaction force traces of 16 male recreational runners during overground running at matched velocity in canvas plimsolls with (red) and without (blue) textured insoles.

Figure 1.

a. b.

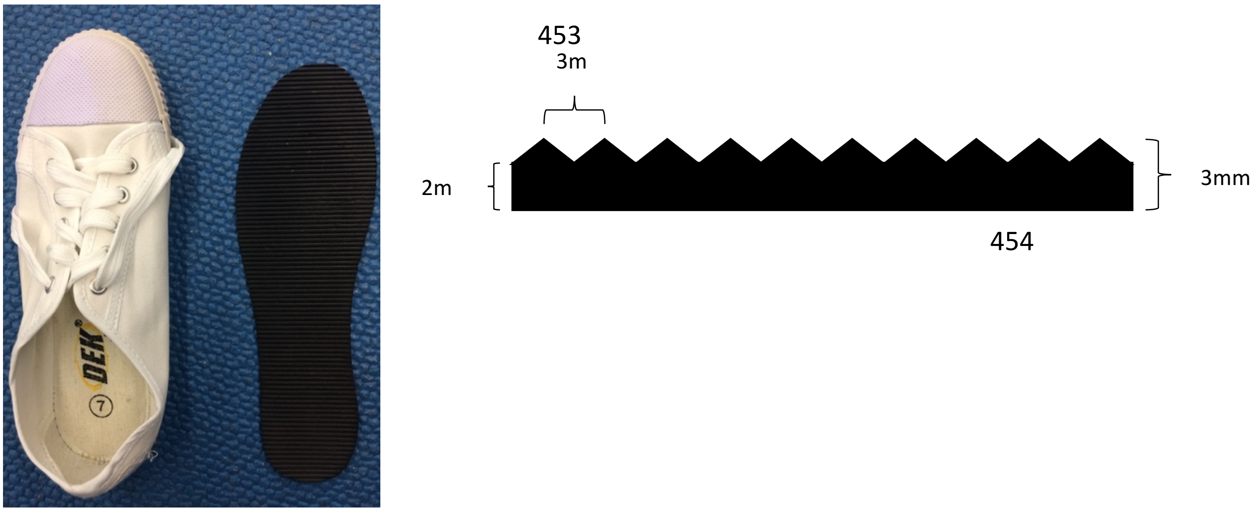


Figure 2.

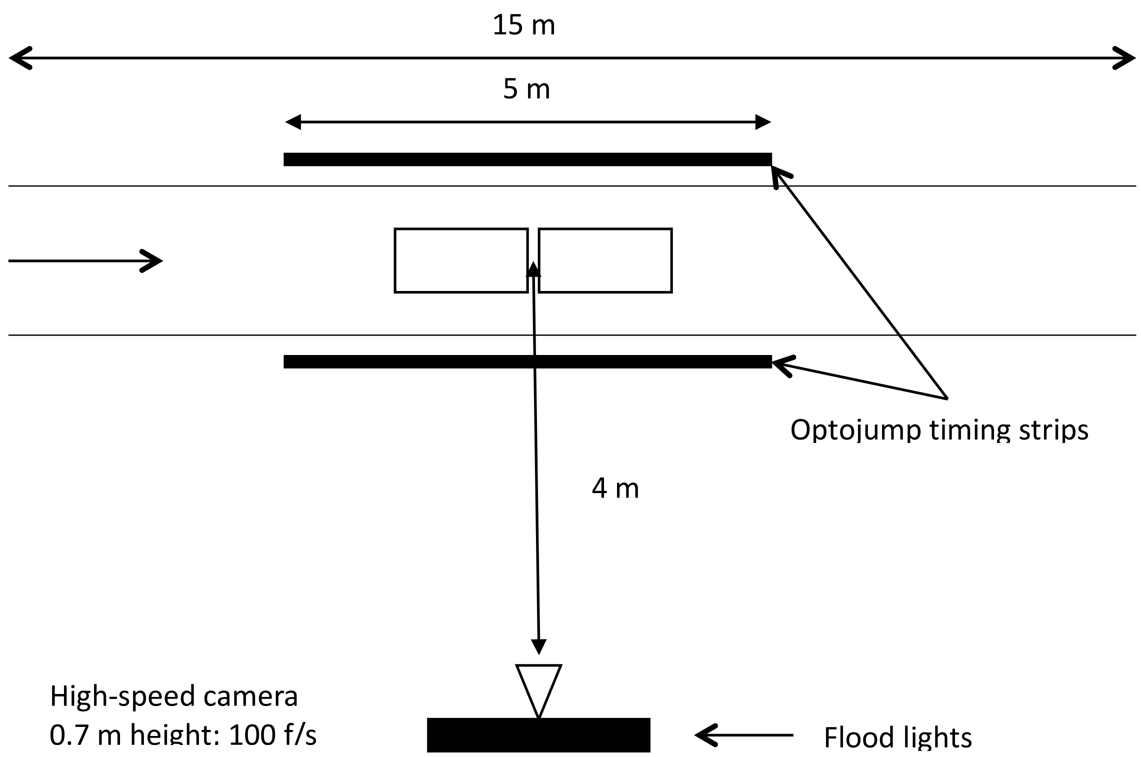
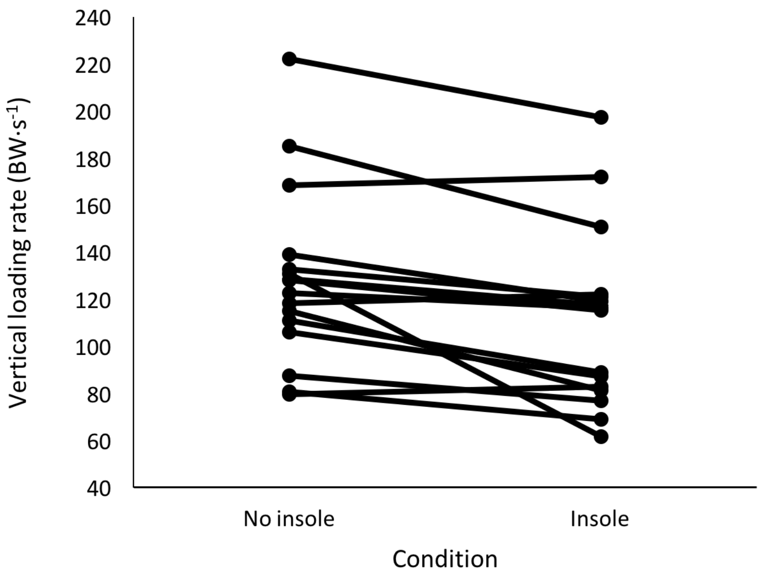

15 m
5 m
Optojump timing strips
4 m
High-speed camera
0.7 m height: 100 f/s
Flood lights

Figure 3.



240
220
200
180
160
140
120
100
80
60
40
Vertical loading rate (BW·s-1)
No insole
Insole
Condition

Figure 4.

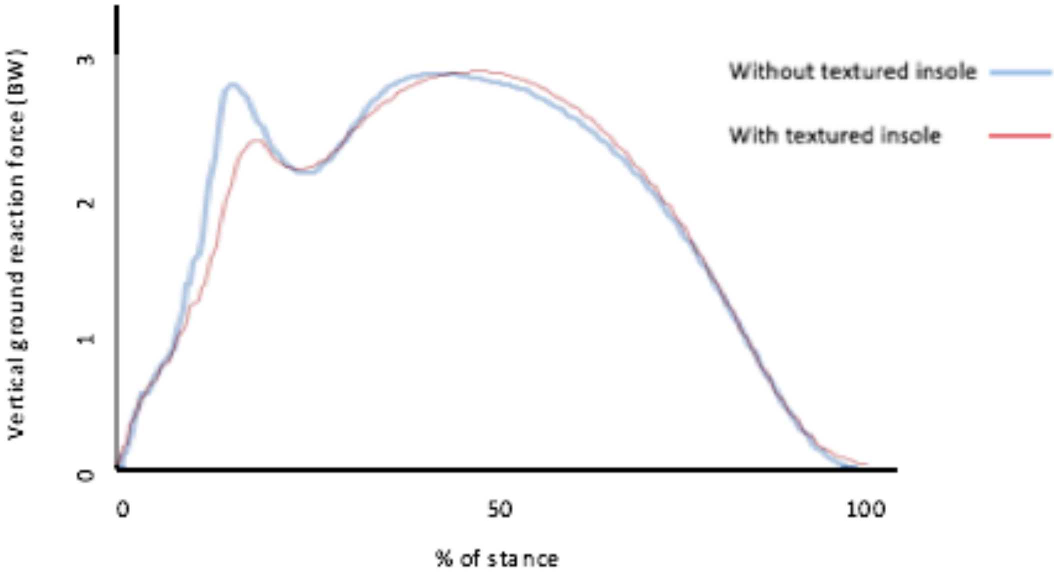

Vertical ground reaction force (BW)
0
1
2
3
0
50
100
% of stance
Without textured insole
With textured insole

Table 1.

	Mean ± SD No insole	Mean ± SD Textured insole	Mean ± SD difference (insole minus no insole)	95% CI of mean difference
Hip angle at footstrike (°)	156.2 ± 8.6	156.4 ± 8.5	0.19 ± 1.99	-0.87 to 1.25
Knee angle at footstrike (°)	164.1 ± 5.1	163.7 ± 4.8	-0.31 ± 3.01	-1.91 to 1.29
Ankle angle at footstrike (°)	86.7 ± 4.8	85.4 ± 4.7	-1.25 ± 2.74	-2.66 to 1.56
Hip angle at COM-A alignment (°)	150.0 ± 8.13	149.8 ± 7.9	-0.27 ± 2.53	-1.62 to 1.08
Knee angle at COM-A alignment (°)	136.7 ± 4.8	135.7 ± 6.5	-0.97 ± 3.25	-2.77 to 0.83
Ankle angle at COM-A alignment (°)	74.7 ± 3.5	73.8 ± 3.9	-0.87 ± 1.84	-1.82 to 0.07