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Title

Effect of shoe cushioning on landing impact forces and spatiotemporal parameters during running: results from a randomized trial including 800+ recreational runners

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Abstract

In a recent randomized trial including 800+ recreational runners, injury risk was lower in those who received the Soft shoe version compared to those using the Hard version (Hazard ratio=1.52; 95% Confidence Interval=1.07-2.16). Here, we investigated the effect of shoe cushioning on ground reaction forces (GRF) and spatiotemporal parameters in the same cohort, with a special focus on Vertical Impact Peak Force (VIPF) and Vertical Instantaneous Loading Rate (VILR). Healthy runners (n=848) randomly received one of two shoe prototypes that differed only in their cushioning properties (Global stiffness: 61±3 and 95±6 N/mm in the Soft and Hard versions, respectively). Participants were tested on an instrumented treadmill at their preferred running speed. GRF data was recorded over 2 minutes. VIPF was higher in the Soft shoe group compared to the Hard shoe group (1.53±0.21 vs. 1.44±0.23 BW, respectively; $p<0.001$). However, the proportion of steps with detectable VIPF was lower in the Soft shoe group (84 vs. 97%, respectively; $p<0.001$) and Time to VIPF was longer (46.9±8.5 vs. 43.4±7.4 milliseconds, respectively; $p<0.001$). No significant differences were observed for VILR (60.1±13.8 vs. 58.9±15.6 BW/s for Soft and Hard shoe group, respectively; $p=0.070$) or any other kinetic variable. These results show that the beneficial effect of greater shoe cushioning on injury risk in the present cohort is not associated with attenuated VIPF and VILR. These GRF metrics may be inappropriate markers of the shoe cushioning-injury risk relationship, while delayed VIPF and the proportion of steps displaying a VIPF could be more relevant.

Key terms: Footwear; Shoe cushioning; Vertical impact peak force; Vertical loading rate

Introduction

The role of running shoes in injury prevention has since long been a hotly debated topic. Running footwear is potentially an extrinsic risk factor that may modify the training load an athlete can tolerate before incurring a running-related injury.[1] However, there is currently only limited evidence on the relationship between shoe features and running-related injury risk.[2, 3] Amongst others, it is currently unclear to what extent shoe cushioning influences injury risk. In a previous randomized trial, we compared two versions of a standard running shoe with a moderate difference in midsole hardness (15%) and did not find any influence on injury risk.[4] In our most recent trial including more than 800 recreational runners, the participants randomly received one of two running shoe models that differed by ~35% in their cushioning properties.[5] A 6-month follow-up revealed that those using the Soft shoe version had a lower injury risk compared to those having received the Hard version (Hazard ratio - HR=1.52; 95% Confidence Interval – 95% CI=1.07 to 2.16; Soft shoe group is the reference). Furthermore, a stratified analysis showed that, in contrast with popular belief, only lighter runners benefited from this protective effect of greater shoe cushioning (HR=1.80; 95% CI=1.09 to 2.98), while no effect was observed in heavier runners (HR=1.23; 95% CI=0.75 to 2.03). This is the first trial ever to demonstrate a difference in injury risk according to shoe cushioning.

The underlying mechanisms that may explain the protective effect of greater shoe cushioning is yet to be uncovered. The use of cushioning systems in running shoes is based on the assumptions that external impact forces relate to injury risk, that footwear cushioning material can reduce these impact forces, and that cushioning itself has no other detrimental effect on injury risk.[6] The current knowledge on the relationship between impact force-related variables, such as vertical impact peak force (VIPF) and vertical instantaneous loading rate (VILR), and injury risk is inconsistent.[3, 7, 8] Small sample sizes, as well as differences in the populations investigated, methods used for shoe characterization (e.g. midsole hardness or global stiffness) and study designs may be the major reasons for inconsistent results and the limited evidence on these potential risk factors.[2, 3, 7] Nevertheless, a meta-analysis[9] revealed that loading rate was higher in runners with a history of stress fracture. A similar effect was found in studies that included runners with all running-related injury types compared with those without injuries, although these conclusions were based exclusively on cross-sectional studies. Additionally, a prospective study demonstrated that VIPF and loading rate were greater in female runners with a medically diagnosed injury compared to those who had never been injured.[10]

The influence of shoe cushioning properties on ground reaction force (GRF) characteristics during running remains controversial. In our previously described trial on 800+ runners, we used a combined epidemiological and biomechanical approach, whereby our two study groups also performed a running test on an instrumented treadmill at baseline to assess GRF and spatiotemporal variables.[11] The main objective of the present study was to seek a functional explanation to the protective effect of the Soft shoe version observed previously.[5] Therefore, we present here a comparison of the kinetic and spatiotemporal data from our two study groups, to investigate the influence of shoe cushioning on running biomechanics. Given that a lower injury risk was observed in the participants allocated to the Soft shoe group[5], and based on current literature findings[9, 10], we hypothesized that VIPF and VILR would be lower in participants using the Soft shoe version. We assumed that the large sample size of 800+ runners combined with a difference in stiffness between the two shoe versions of 35% would reveal even minor discrepancies in the GRF and spatiotemporal characteristics. Since we previously found that the protective effect of shoe cushioning was confined to lighter runners, we conducted separate comparisons of biomechanics within subgroups based on body mass.

Methods

Study design

This was a participant- and assessor-blinded randomized trial with a biomechanical running analysis at baseline and a 6-month follow-up on running exposure and injury risk, comparing two running shoe prototypes which only differed regarding their cushioning properties. The present contribution focuses on the biomechanical running analysis performed at baseline, and therefore, the effect of shoe cushioning on GRF and spatiotemporal variables. The protocol was approved by the National Ethics

Committee for Research (ref. 201701/02 v1.1). All volunteers received a full description of the protocol[11] and provided written informed consent for participation. The trial was registered on www.clinicaltrials.gov (identifier: NCT03115437). The study is reported in accordance with the CONSORT statement.[12]

Participants

Leisure-time runners were recruited through advertisements in public media and social networks in Luxembourg from September 2017 to January 2018. An a priori sample size calculation estimated that 802 participants (401 per group) were required for the trial.[11] Volunteers were included if they were in good health, aged 18-65 years, and capable of performing 15 minutes of consecutive treadmill running. Exclusion criteria were any medical contraindication to perform running activity (i.e. cardiovascular/respiratory disease or running impeding injury), prior (<12 months) surgery at the lower limbs or back region, use of orthopedic insoles for running or any running impeding injury over the previous month.

Intervention

Two versions (Hard and Soft cushioning) of an anonymized conventional running shoe model were specifically designed and provided by a sport equipment manufacturer. Apart from the cushioning properties, the two versions were identical, with a mass of 337±17 grams, heel-to-toe drop of 10 mm and stack height at the heel of 34 mm. Shoe stiffness at the heel was characterized on a subset of 40 shoes (10 pairs per condition) using a standardized protocol.[13] Global stiffness differed by 35.4% (94.9±5.9 and 61.3±2.7 N/mm in the Hard and Soft versions, respectively). Further characteristics can be found elsewhere.[5, 11] Participants were stratified according to sex, known to influence many anthropometric characteristics, and blinded regarding their group allocation. Two pre-established randomization lists (block size = 40) were used to allocate one of the two shoe versions to each participant. The shoe code was broken after completion of data collection.

Procedures

Prior to follow-up, the participants filled out a questionnaire evaluating their running history, underwent anthropometric assessments and performed a baseline biomechanical running test during a single session at the laboratory. Height, body mass, fat mass proportion (Tanita SC-240 MA) and leg length (measured between the anterior superior iliac spine and the medial malleolus, in supine position) were measured prior to warm-up. The distance between the greater trochanter and the ground was also measured (standing position) to assess leg stiffness.[14] The baseline biomechanical running analysis was performed on a split-belt treadmill instrumented with force plates (M-Gait, MotekForce link Amsterdam, The Netherlands) using the allocated shoe type. The protocol consisted of a 3-minute warm-up, followed by an 8-minute habituation phase at the self-declared preferred running speed[15], followed by a 2-min data collection phase at the same running speed. The full 2-minute record was included in the analysis.

Signal processing

The 3-dimensional ground reaction forces were recorded at 2 kHz and imported into a custom-programmed Matlab software (Matlab R2014a, MathWorks, Netherlands). Participant's body weight (BW, in N) was obtained by the average vertical signal (Fz) recorded during 5 seconds of quiet stance. A bidirectional low-pass filter (cut-off frequency of 30 Hz, 2nd order Butterworth) was then applied to the force data. Initial contact (IC) and toe-off (TO) events were identified by Fz exceeding or falling below a 20-N threshold.[16] Stride time (ST, in ms) was defined as the time interval between two consecutive IC events from the same foot, and contact time (CT, in ms) as the time interval between IC and TO. Flight time (FT, in ms) was calculated as the difference between ST and CT, and duty factor (DF, in %) as the ratio between CT and ST. Step length (SL, in m) and step cadence (CAD, in steps.min^{-1}) were other spatiotemporal gait parameters analyzed.

The Matlab "findpeaks" function was used to detect peaks on the Fz curve. The highest Fz_{max}-value recorded during stance phase was defined as Peak vertical force (PVF, in BW). We also checked that PVF was detected in a window of +/- 50 milliseconds around mid-stance. VIPF (in BW) was defined as the first peak of the Fz curve (Fz_{peak1}) in those steps displaying 2 peaks in the Fz-record (Figure 1). If during a given step only one peak was present, that peak was defined as PVF, and that step was marked as having no VIPF. All curves with corresponding peaks (VIPF and PVF) were visually inspected for each participant and manually confirmed. Time to PVF (t_{PVF}, in ms) was defined as the time interval between IC and PVF, and time to VIPF (t_{VIPF}, in ms) as the time interval between IC and VIPF. VILR (in $BW.s^{-1}$) was calculated as VILR=max(dFz / dt), where ($t_{IC}<t<t_{VIPF}$) for steps with a detectable VIPF and where ($t_{IC}<t<t_{PVF}$) for steps without a VIPF. Vertical average loading rate (VALR, in $BW.s^{-1}$) was calculated between 20 and 80% of the period between IC and VIPF (Figure 1)[17], or between IC and PVF for steps without VIPF. Peak power was defined as the highest value of the power curve. Vertical oscillation of the center of mass (VO, in mm) was calculated as the difference between minimal and maximal vertical position of the center of mass during a step. Vertical stiffness (Kvert, in $kN.m^{-1}$) and leg stiffness (Kleg, in $kN.m^{-1}$) were calculated according to Morin et al.[14] The vertical GRF (i.e. Fz-based) variables were normalized by the participant's body weight. Positive and negative work and vertical impulse were calculated as the area under the power-time and Fz-time curves, respectively. Discrete variables were calculated on each gait cycle, and then averaged per subject. Data from both limbs were averaged.

Insert Figure 1 about here.

Statistics

An analysis of variance (ANOVA) was used to compare the means between the two study groups, with speed as co-variable given that the participants were tested at their self-declared preferred running speed. The significance level was set at $p<0.05$. Effect sizes were reported using Cohen's d[18], and were interpreted as negligible (0 to <0.15), small (0.15 to <0.40), medium (0.40 to <0.75), large (0.75 to <1.10), and very large (≥1.10). The Kruskal-Wallis test was used to compare the two groups for non-normally distributed variables. Additionally, a stratified analysis was performed to investigate if the effect of shoe cushioning on running biomechanics is modified by body mass (with speed as co-variable). Participants were classified as light or heavy runners using the median value of body mass from the 2 groups combined as cut-off, independently in men and women.[5] All analyses were performed using STATA/SE V.15.

Results

Participants

From the 1107 volunteers who registered to the study, 874 were randomly allocated to the study groups and performed the running test in the laboratory. As 26 participants were excluded from the analysis of the association between shoe cushioning and injury risk[5], the present results eventually include 848 runners. A flow chart is presented in Supplementary material – Figure 1. The participants' characteristics are presented in Table 1. The number of steps analyzed per participant was 325±19 (range: 278 to 393 steps), for a total of >275 000 steps analyzed.

Insert Table 1 about here.

Spatiotemporal and kinetic variables

Descriptive and inferential statistics for the spatiotemporal and kinetic variables are presented in table 2. No significant difference was observed between the two groups for the spatiotemporal variables. A significantly higher VIPF (95% CI: 0.07 to 0.13 BW; 6.9%) was observed in the Soft shoe group compared to the Hard shoe group, and the effect size was medium (Figure 2A). A VIPF could not be detected during each stance phase and was not present at all during the 2-min recording for 24 participants (13 and 11 participants for the Soft and the Hard shoe groups, respectively). Supplementary material - Figure 2 illustrates the vertical GRF curves from 3 participants with 0, 50 and 100% steps with VIPF, respectively. The proportion of steps with detectable VIPF was lower ($p<0.001$) in the Soft shoe group. A longer time to VIPF was observed (95% CI: 2.4 to 4.4 milliseconds; 7.8%; medium effect) in the Soft shoe group (Figure 2B). No significant difference was observed for VILR (Figure 2C) or for the other kinetic variables.

Insert Table 2 about here.

Insert Figure 2 A, B and C about here.

Stratified analysis by body mass category

When stratifying the participants according to body mass (Supplementary material - Table 1), the differences between the two shoe groups regarding VIPF, the proportion of steps with detectable VIPF and the time to VIPF remained statistically significant in both lighter and heavier runners. No other difference between the shoe groups was observed in either of the body mass categories, except for a slightly longer time to peak force observed in the Hard shoe group among the heavier runners (95% CI: 0.2 to 5.7 milliseconds, 2.2%, Cohen's *d*: 0.08, negligible effect).

Discussion

This is the first randomized trial investigating the influence of shoe cushioning on running biomechanics in a large cohort of 800+ recreational runners, combined with a 6-month prospective follow-up investigating injury risk. Given that a lower injury risk was previously observed in the Soft shoe group of the same cohort[5], and considering prior literature findings on impact forces and injury risk[9, 10], we hypothesized that VILR and VIPF would be lower in the Soft shoe group. Contrary to our expectations, the main finding was that VIPF was higher in the Soft shoe group compared to the Hard shoe group. This contrasts with previous studies suggesting that a higher VIPF could be a potential risk factor for running injury.[10, 19] Another important finding was that VILR did not differ between the two groups. The lower proportion of steps with a VIPF and longer time to VIPF in the Soft shoe group were the only other group differences observed in the kinetic variables. No group differences were found regarding the spatiotemporal variables. Thus, our findings suggest that the beneficial effect of greater shock absorption properties on injury risk previously reported in the same cohort cannot be explained by a decrease in VIPF or VILR. It seems that a more in-depth biomechanical analysis is needed to unravel the underlying mechanism involved.[5]

VIPF, VILR and greater cushioning

I*n vitro*, lower impact forces are observed in softer or more compliant shoes.[20] However, previous *in vivo* studies investigating the effect of shoe cushioning on vertical GRF did not provide consistent results.[7] In particular, recent research has revealed that VIPF is increased when running in shoes with greater cushioning[21-24], which is consistent with our findings. First, a cross-sectional study comparing 3 prototypes (Asker C-40, C-52 and C-65, midsole hardness respectively) showed that lower midsole hardness was associated with higher VIPF.[21] Several studies comparing maximalist shoes (i.e. running shoes with extreme cushioning) to traditional shoes provided additional insight on vertical GRF features.[22-24] During downhill treadmill running, maximalist shoes (Hoka One One) induced a higher VILR compared to traditional running shoes, although no difference was observed during level running.[22] Consistently, higher results for VIPF and VILR were observed in maximalist shoes compared to traditional shoes, both before and after a 5k-run.[24] In another study, maximalist shoes showed greater VIPF and VILR at greater running speed (14.5 km/h), but only VIPF was higher in the maximalist shoes at lower speed (10 km/h).[23] The latter observation is consistent with the present study where a higher VIPF was observed with greater cushioning and no difference in VILR was found at an average running speed of 9.9(±1.5) km/h (Table 2). Thus, the present findings confirm that greater shoe cushioning induces higher VIPF in running, an observation previously presented as the "impact peak anomaly".[20] VIPF in the vertical GRF waveform during running is composed of a high-frequency load ("true" impact) resulting in an impact peak, and low-frequency (non-impact) loads resulting in a mid-stance peak.[20] Frequency domain analyses of GRF during running revealed that softer shoes attenuate the magnitude of the high-frequency impact peak.[20] Furthermore, softer shoes also delay this high-frequency impact peak. Consequently, the attenuated high-frequency load is summed with low-frequency loads of greater magnitude, and the contribution of non-impact force components to VIPF is increased. In other words, while the "true" impact peak is decreased, the observed VIPF may be increased because of the relatively greater contribution of the low frequency loads.[20] Another consequence of the delayed high-frequency component resulting from greater cushioning is that the observed VIPF is also delayed, as was observed in the Soft shoe group here. This may also explain why no difference was observed in VILR here. Indeed, the three variables (i.e. VILR, VIPF, and time to VIPF) are highly interconnected, in that a greater VIPF combined with a longer time to VIPF may result in a similar loading rate.

Detection of VIPF

VIPF could not systematically be identified in all participants. Our results showed that the proportion of steps with VIPF was lower in the Soft shoe group compared to the Hard shoe group (Table 2). A previous study reported that VIPFs, defined as local maxima during the early stance phase (25%), were present in 96% of steps in rearfoot strikers, but only in 16 and 32% in forefoot strikers in shod and minimalist conditions, respectively.[17] The present study suggests that not only foot strike pattern, but also shoe cushioning influences this biomechanical aspect of running. Another plausible explanation could be found again based on the frequency domain decomposition of the vertical GRF waveform.[20] Because of the increased time to VIPF in shoes with greater cushioning, the contribution of the low-frequency load component to VIPF is higher, and VIPF could therefore be more difficult to detect (Supplementary material - Figure 2B). Our results suggest that delayed VIPF and lower proportion of steps displaying VIPF as a result of greater cushioning may have relevance in terms of injury risk and deserve further study in that respect.

Practical implications

Cushioning systems were introduced in footwear to reduce the magnitude of impact forces and/or modify their timing characteristics. In the present study, we found that greater cushioning was associated with higher VIPF (Table 2 and Figure 2A). The fact that VIPF derives from a superimposition of the non-impact force components on the impact force can account for this anomalous effect of shoe cushioning on the transient peak of the GRF, but suggests that VIPF is not a valid indicator of running shoe impact attenuation.[20] There is also a discrepancy in the scientific literature on the association between impact forces and injury risk. So far, only loading rate and VIPF have been associated with injury risk in running, specifically stress fracture risk.[9, 10] Conversely, some prospective studies suggested that greater loading rate may have a protective effect.[25, 26] This discrepancy may result from the complex relationship between external force measurement and the resulting tissue-specific stress, which also depends on many other individual factors (e.g. tissue size, geometry, tissue properties…). The suitability of vertical GRF to assess the loading of internal structures has recently been questioned, as GRF metrics were not strongly correlated with increases in tibial load metrics.[27] Our results support the suggestion that GRF metrics such as VIPF and VILR may not be appropriate indicators of injury risk, while time to VIPF and the percentage of steps with detectable VIPF could be of relevance here. External impact forces may only reveal part of the reality. For instance, a recent simulation study in 40 recreational runners comparing three midsole cushioning conditions found that softer midsoles reduced contact forces and loading rates at the ankle, but the effect was less consistent among the 3 conditions at the knee and hip.[16] Consequently, it is necessary to undertake a more detailed analysis of running biomechanics involving lower limb joint kinematics and kinetics to investigate if internal load distribution is different in the two shoe conditions.

Strengths and limitations

This study compared two shoe versions with cushioning properties that remain within the range of values of shoes available on the market, including racers and maximalist shoes. One of the main strengths of this trial is the innovative design investigating the influence of shoe cushioning on both running biomechanics and injury risk over 6 months in a very large cohort of runners. Another strength is the high number of steps that were analyzed per participant (325±19 steps) in the allocated shoe conditions. Conversely, the analysis of running biomechanics on an instrumented treadmill does not inform on how surface, slope, or fatigue might alter shoe cushioning effects on running biomechanics. Nevertheless, the laboratory setting and the large number of steps analyzed guarantee an accurate evaluation of each participant's running technique in standardized conditions, providing a robust between-group comparison with a low risk of confounding. Our between-group comparison may be seen as a disadvantage, because the inter-subject variability may partially conceal the variability related to the shoe effect. However, our study sample size and the robustness of the randomization process allowed minimizing the risk of confounding bias. More competitive runners might be underrepresented in this study, because of a lower readiness to comply with the study requirements, and the influence of shoe cushioning on running biomechanics might be greater at higher speeds. However, these competitive runners might not represent the main proportion of recreational runners. Also, our study participants showed some degree of running experience with 52% reporting >6 years of previous running training (Table 1) and 70% practicing at least twice a week.

Conclusion

VIPF was higher in the group of recreational runners who received the Soft shoe version compared to those with the Hard shoe version, while no difference was found for VILR. On the other hand, time to VIPF was longer and the proportion of steps with detectable VIPF was lower in participants with the Soft shoe version. As our previous prospective follow-up of this cohort revealed that injury risk was lower in the group with the Soft shoe version, the current results show that the beneficial effect of greater cushioning cannot be explained by a decrease in VIPF or VILR. Taken alone, these GRF metrics are not appropriate markers to illustrate the relationship between shoe cushioning and injury risk, while delayed VIPF and the proportion of steps displaying a VIPF may be of relevance here.

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Table 1: Participants' characteristics and running history for the 2 study groups (n=848).

Characteristics	Unit/Qualifier	Soft shoe group (n=428)	Hard shoe group (n=420)
Participants' characteristics			
Age	Years	40.4±10.2	40.5±9.8
Sex	Male	259 (60.5%)	260 (61.9%)
	Female	169 (39.5%)	160 (38.1%)
Height	cm	174±9	174±9
Body mass	kg	73.2±12.8	73.3±12.4
Proportion of fat mass	%	22.7±7.2	22.4±7.5
Leg length	cm	90.5±5.5	90.7±5.3
Running history			
Running experience [a]	Years	6 [0-45]	6 [0-40]
Regularity (last 12 months) [a]	Months	12 [0-12]	12 [0-12]
Running frequency [a]	Sessions.week^{-1}	2 [1-3]	2 [1-3]
Mean session distance [a]	km	8 [6-10]	9 [6.5-10]
Mean running speed	km.h^{-1}	9.8±1.7	9.9±1.7
Participation in competitions	Yes	253 (59.1%)	246 (58.6%)
	No	175 (40.9%)	174 (41.4%)
Preferred running distance [a, b]	km	10 [3-50]	10 [5-50]
Best performance on 10 km [c]	min	52±9	52±9

[a] Non-normally distributed variables presented as median [interquartile range]; [b] 364 missing data; [c] 368 missing data.

Table 2: Effect of shoe version on spatiotemporal variables and running kinetics (n=848).

Characteristics	Unit	Soft shoe group (n=428)	Hard shoe group (n=420)	Mean absolute difference	P-value	*d*
Spatiotemporal variables						
Speed	$Km.h^{-1}$	9.8±1.5	9.9±1.5	0.1	0.591	0.04
Step cadence	$steps.min^{-1}$	164±9	164±10	0.4	0.371	0.05
Step length	m	1.00±0.14	1.01±0.15	<0.01	0.435	0.05
Contact time	ms	291±36	291±38	<0.1	0.525	<0.01
Flight time	ms	442±39	444±38	1.9	0.570	0.05
Duty factor	%	39.7±4.3	39.6±4.3	0.1	0.973	0.03
Vertical oscillation of CoM	mm	76±13	77±13	1.0	0.389	0.07
Kinetic variables						
Vertical impact peak force [a]	BW	1.53±0.21	1.44±0.23	0.10	<0.001*	0.44
Steps with VIPF [b]	%	84 [39-98]	97 [61-100]	/	<0.001*	/
Time to VIPF [a]	ms	46.9±8.5	43.4±7.4	3.4	<0.001*	0.43
Peak vertical force	BW	2.21±0.23	2.23±0.24	0.02	0.252	0.08
Time to peak force	ms	126±18	127±17	1.4	0.064	0.08
Vertical instant. loading rate	$BW.s^{-1}$	60.1±13.8	58.9±15.6	1.2	0.070	0.08
Vertical average loading rate	$BW.s^{-1}$	43.0±10.7	43.2±12.0	0.2	0.969	0.08
Peak power	$W.BW^{-1}$	0.92±0.20	0.94±0.21	0.2	0.101	0.11
Positive work	$J.kg^{-1}$	0.76±0.13	0.77±0.13	0.01	0.357	0.07
Negative work	$J.kg^{-1}$	0.75±0.13	0.76±0.12	0.01	0.316	0.08
Vertical impulse	$N.s.BW^{-1}$	0.36±0.02	0.36±0.02	<0.01	0.325	0.05
Vertical stiffness	$kN.m^{-1}$	37.5±5.2	37.1±5.1	0.4	0.116	0.08
Leg stiffness	$kN.m^{-1}$	15.2±2.5	15.2±2.6	<0.1	0.870	0.01

[a] 24 missing values (i.e. no Vertical impact peak force could be identified); [b] Non-normally distributed variable presented as median [interquartile range], and group difference was tested using the Kruskal-Wallis test; * Statistically significant group difference; d: Cohen's *d*; CoM: Center of Mass; ms: milliseconds; mm: millimeters; VIPF: Vertical Impact Peak Force; BW: Bodyweight; ms: milliseconds.

Figure 1. Schematic illustration of outcome variables derived from the vertical ground reaction force (GRF) curve. VIPF: Vertical Impact Peak Force; PVF: Peak Vertical Force; VILR: Vertical Instantaneous Loading Rate; VALR: Vertical average loading rate; Fz: Vertical force signal; BW: Body weight. This illustration is not representative for steps without VIPF.

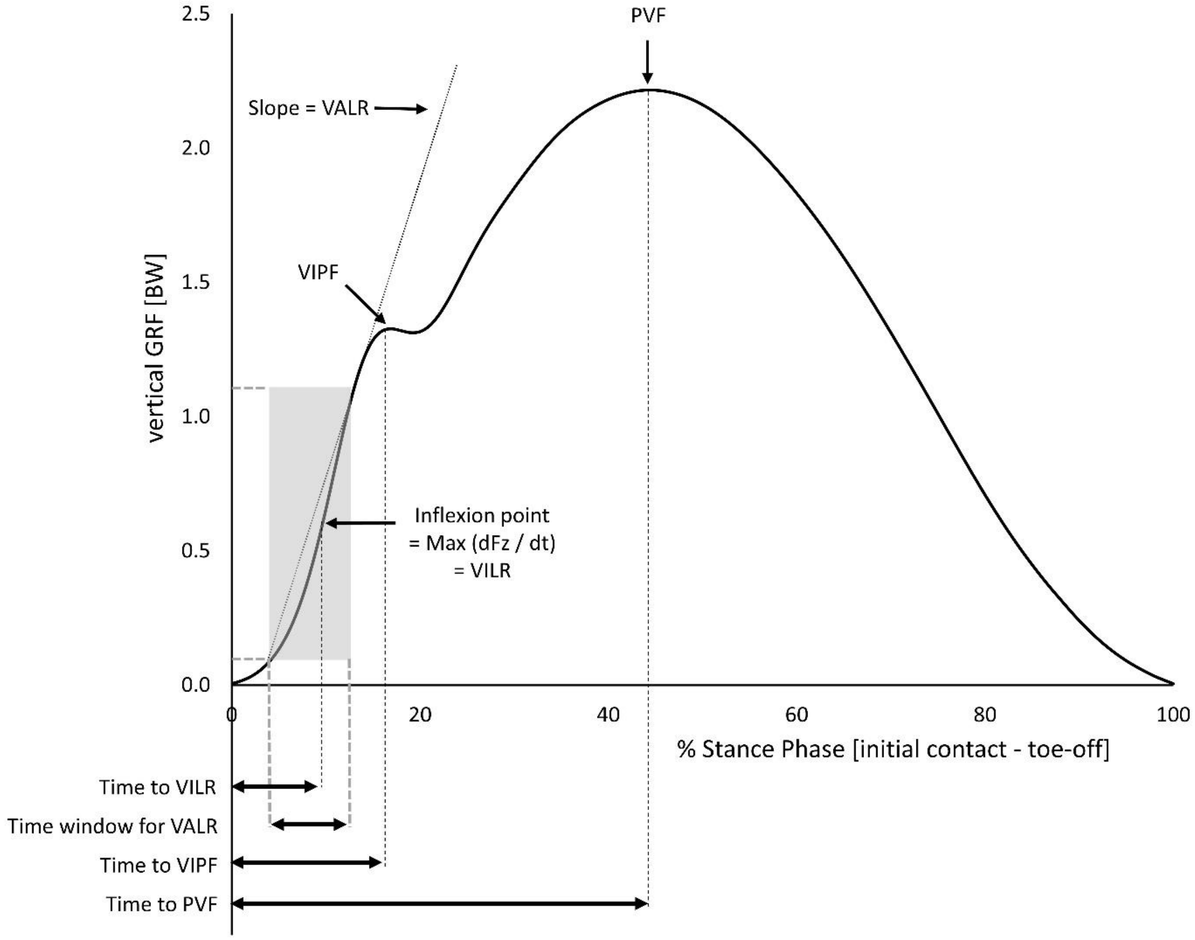
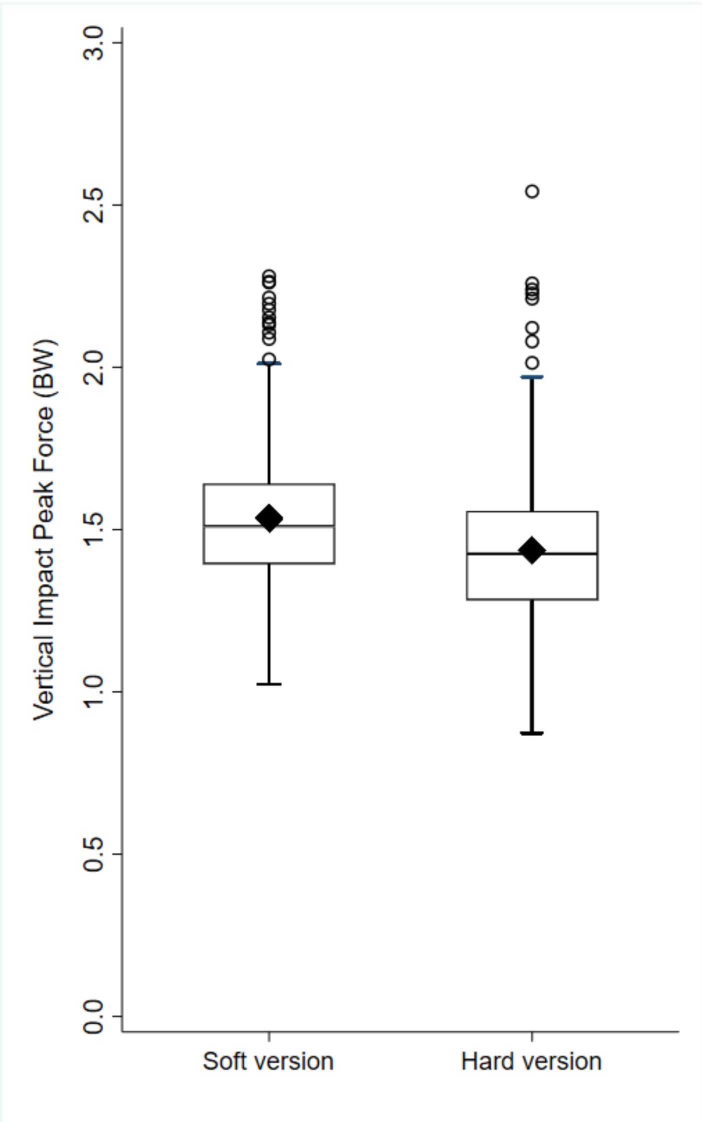
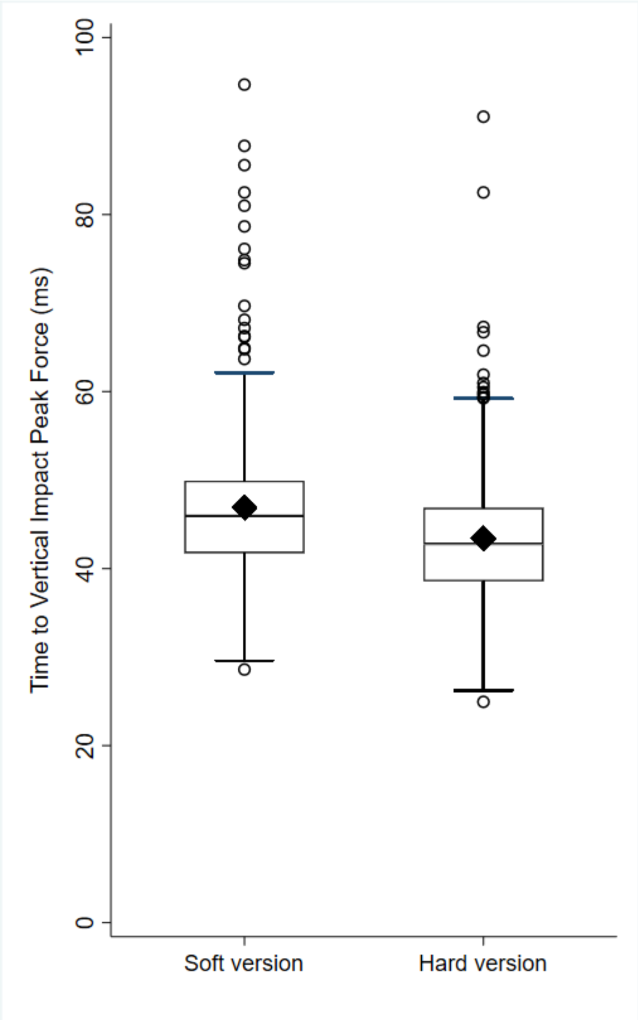


Figure 2 A, B and C. Box plots for Vertical Impact Peak Force (BW; panel A, p<0.001), Time to Vertical Impact Peak Force (ms, panel B, p<0.001) and Vertical Instantaneous Loading Rate ($BW.s^{-1}$, panel C, p=0.071) in the two experimental groups (n=428 and 420 for the Soft and Hard shoe group, respectively). The lower and upper box boundaries indicate the 25th and 75th percentiles, respectively, the middle line inside the box represents the median, and the filled diamond is the mean. Whiskers below and above the boxes represent the 25th percentile – 1.5*interquartile range (IQR) and 75th percentile + 1.5*IQR, respectively. Empty circles are data falling outside of the whiskers.

A

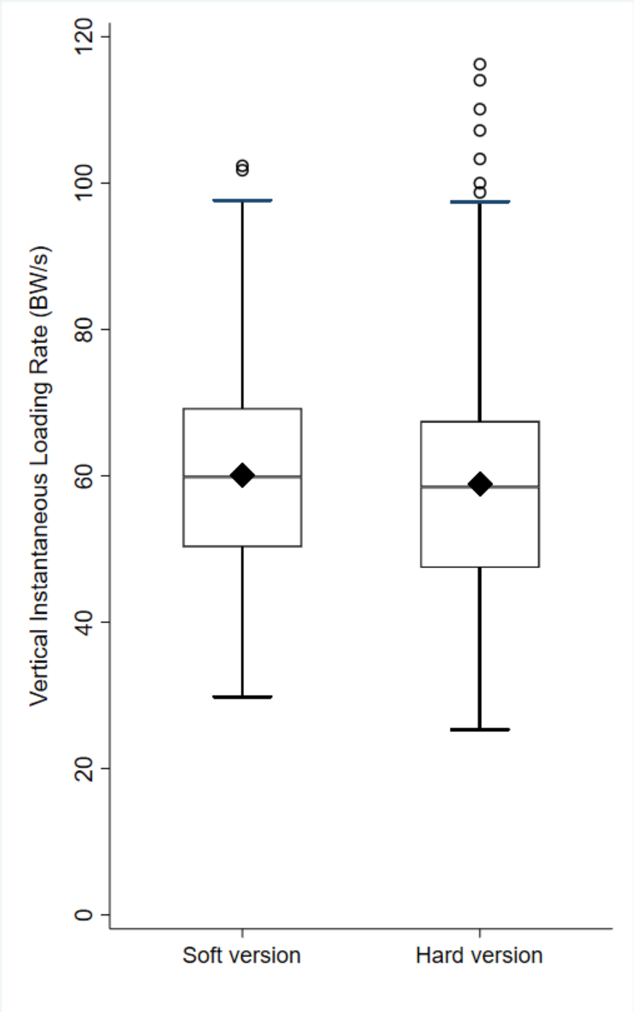


B



Time to Vertical Impact Peak Force (ms)
100
80
60
40
20
0
Soft version
Hard version

C



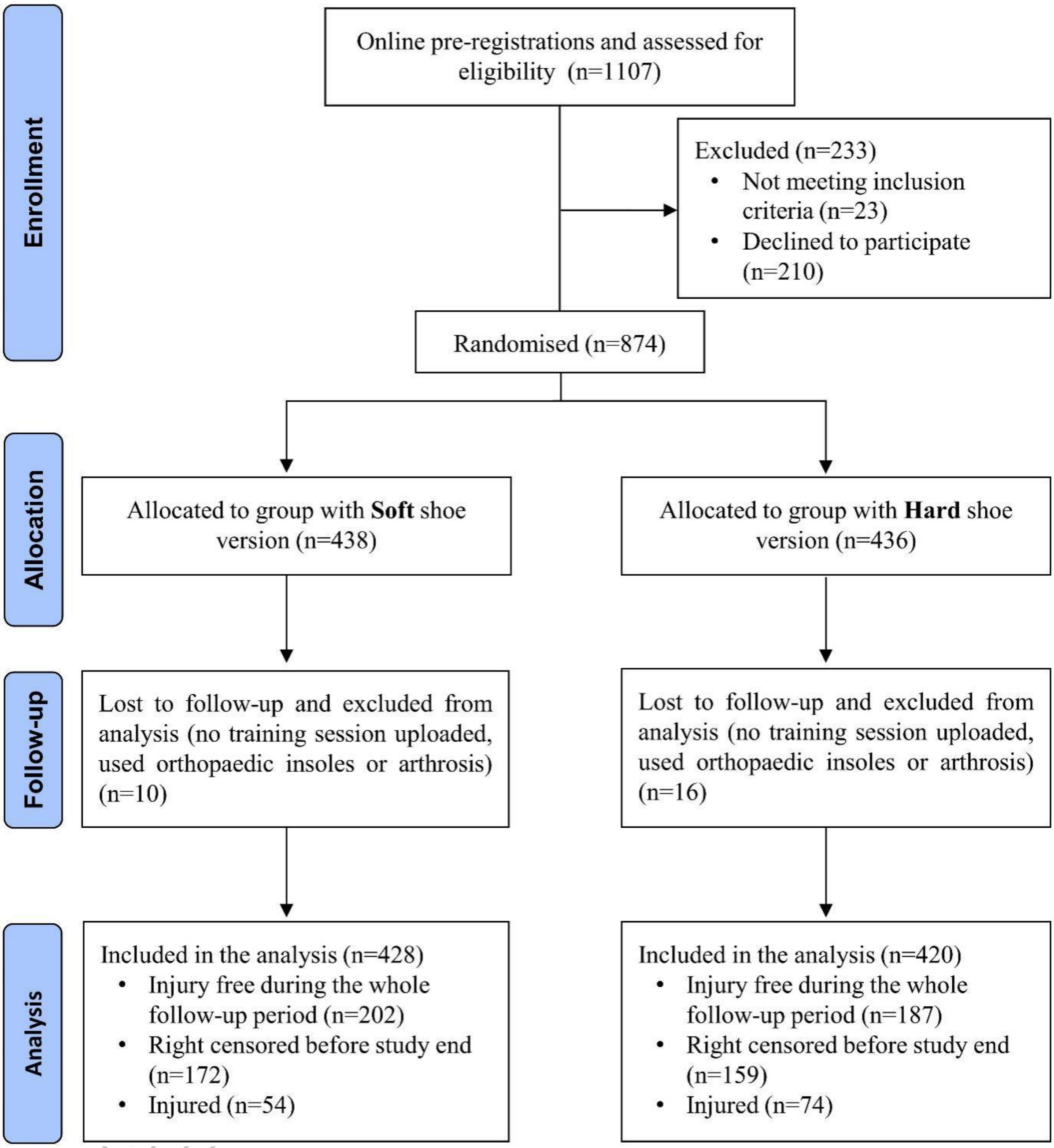
Vertical Instantaneous Loading Rate (BW/s)
0
20
40
60
80
100
120
Soft version
Hard version

Supplementary material - Table 1: Effect of shoe version on spatiotemporal variables and running kinetics stratified by body mass categories (n=848).

Characteristics	Unit	Lighter participants			Heavier participants		
		Soft shoe group (n=203)	*Hard shoe group (n=220)*	*P-value*	*Soft shoe group (n=225)*	*Hard shoe group (n=200)*	*P-value*
Spatiotemporal variables							
Speed	$Km.h^{-1}$	10.2±1.5	10.2±1.6	0.984	9.5±1.4	9.6±1.5	0.756
Step cadence	$steps.min^{-1}$	166±9	165±9	0.578	163±9	162±10	0.338
Step length	m	1.03±0.15	1.03±0.15	0.695	0.97±0.13	0.98±0.14	0.348
Contact time	ms	275±30	276±31	0.592	305±36	307±38	0.219
Flight time	ms	450±38	451±37	0.824	435±39	436±38	0.743
Duty factor	%	38.0±3.7	38.0±3.7	0.864	41.2±4.2	41.3±4.2	0.640
Vertical oscillation of CoM	mm	78±13	79±12	0.540	75±14	75±13	0.668
Kinetic variables							
Vertical impact peak force [a]	BW	1.56±0.23	1.47±0.25	<0.001*	1.51±0.19	1.40±0.20	<0.001*
Steps with VIPF [b]	%	86 [42-99]	96 [61-100]	<0.001*	84 [35-98]	97 [60-100]	<0.001*
Time to VIPF [a]	ms	44.0±6.7	41.3±6.8	<0.001*	49.6±9.1	45.8±7.4	<0.001*
Peak vertical force	BW	2.29±0.22	2.31±0.22	0.397	2.14±0.22	2.15±0.22	0.774
Time to peak force	ms	121±16	122±15	0.330	131±18	133±18	0.032*
Vertical instant. loading rate	$BW.s^{-1}$	63.1±14.5	61.3±16.9	0.168	57.3±12.6	56.2±13.6	0.176
Vertical average loading rate	$BW.s^{-1}$	46.2±11.2	45.8±13.0	0.735	40.1±9.4	40.3±10.2	0.994
Peak power	$W.BW^{-1}$	0.98±0.20	1.00±0.21	0.177	0.86±0.20	0.87±0.20	0.575
Positive work	$J.kg^{-1}$	0.78±0.13	0.79±0.12	0.524	0.75±0.14	0.75±0.13	0.638
Negative work	$J.kg^{-1}$	0.77±0.12	0.77±0.12	0.452	0.73±0.13	0.74±0.12	0.627
Vertical impulse	$N.s.BW^{-1}$	0.36±0.02	0.36±0.02	0.528	0.37±0.02	0.37±0.02	0.313
Vertical stiffness	$kN.m^{-1}$	39.0±5.3	38.5±5.1	0.253	36.1±4.7	35.6±4.7	0.122
Leg stiffness	$kN.m^{-1}$	16.0±2.6	15.9±2.7	0.784	14.5±2.1	14.3±2.3	0.514

[a] 24 missing values (i.e. no Vertical impact peak force could be identified); [b] Non-normally distributed variable presented as median [interquartile range], and group difference was tested using the Kruskal-Wallis test; * Statistically significant group difference; CoM: Center of Mass; ms: milliseconds; mm: millimeters; VIPF: Vertical Impact Peak Force; BW: Bodyweight; ms: milliseconds.

Supplementary material - Figure 1. Flow chart of volunteers and study participants.



Supplementary material - Figure 2. Vertical Ground reaction Force (GRF) curves from 3 participants with 0% (panel A), 50% (panel B) and 100% (panel C) of their steps with a VIPF identified during stance phase, respectively. Solid line is the participant's ensemble average mean, and dashes lines are 1 SD below and above the mean.