Title

The effects of running shoe stack height on running style and stability during level running at different running speeds

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Abstract

The footwear market contains a wide variety of running shoe solutions aiming at optimizing performance and minimizing injuries. Stack height is one of the most highly discussed design features of running shoes, but its effects are not yet well understood. This study investigated the effects of different shoes differing in their stack heights (H: 50 mm, M: 35 mm & L: 27 mm) on running style and stability during treadmill running at 10 and 15 km/h. A total of 17 healthy experienced runners participated in this study. The kinematic data were recorded with a 3D motion capturing system. The running style was investigated by a dual-axis framework with duty factor and leg length normalized to step frequency (SF_{norm}). Additionally, the ratio of landing to take-off duration, the lower body joint angle time series in the sagittal and frontal planes, the vertical center of mass oscillation (COM_{osc}), and the stiffness parameters (k_{ver} & k_{leg}) were compared for different conditions. The stability was analyzed using linear (i.e. discrete frontal ankle parameters) and nonlinear methods (i.e. Maximum Lyapunov Exponent for local dynamic stability of head, trunk, hip, and foot, and detrended fluctuation analysis of stride time). H resulted in longer steps with longer ground contact relative to stride time, and a higher COM_{osc} comapred to L; and led to a longer foot eversion during stance compared to M. In addition, the local dynamic stability of the hip decreased with H in comparison with L. The higher stack heights (≥ 35 mm) led to a lower SF_{norm} at 15 km/h but not at 10 km/h. The remaining shoe effects were independent of the running speed. Findings showed that changes in stack height can affect running style. Furthermore, the highest stack height resulted in instabilities in some of the stability parameters which may be a critical issue in terms of injuries and performance. However, this study did not include joint load analysis or running performance measures such as VO_2. Future studies may benefit from the combination of analysis approaches to better understand stack height effects on running injuries and performance.

Keywords:

joint kinematics, midsole thickness, advanced footwear technology, treadmill, NonLinear Analysis, Ankle stability, Maximum lyapunov exponent (MLE), Detrended fluctuation analysis (DFA)

1 Introduction

The footwear market is flooded with running shoe solutions that combine various features, such as midsole stiffness, shape of toe box, stack height and heel-to-toe drop. Ultimately, running shoes are optimized to help improve running performance as well as avoid injuries (Hoitz et al., 2020; Mai et al., 2023). Despite a high number of studies, there is still an ongoing debate on what effects different shoe features have on running performance and injuries (Burns & Tam, 2020; Willwacher & Weir, 2023). On this basis, it is crucial to evaluate the effects of different shoe features in detail to understand their biomechanical function (Mai et al., 2023).

Stack height is a highly discussed feature of running shoes, especially since it is limited by the new World Athletics regulation (World Athletic Council, 2022). The actual effects of stack height on running performance and injuries are not yet well understood (Barrons et al., 2023a, 2023b; Hoogkamer, 2020; Ruiz-Alias et al., 2023a; Ruiz-Alias et al., 2023b; Willwacher & Weir, 2023). Various studies reported that increased stack height may lead to performance increases, particularly due to elongated effective leg length (e.g., Burns & Tam, 2020; Ruiz-Alias et al., 2023a). However, there are also studies suggesting that stack height changes alone cannot be sufficient to reduce metabolic cost (Bertschy et al., 2023). Furthermore, the added mass due to a higher stack height may also impair performance by decreasing economy (Burns & Tam, 2020; Hoogkamer, 2020). Besides the running economy perspective, higher stack heights may also decrease ankle frontal plane stability (e.g., Hoogkamer, 2020; Ruiz-Alias et al., 2023a), which may be a critical issue in terms of running performance and injuries. With respect to stack height, optimum levels possibly exist for certain conditions (e.g., running speed, stiffness of the ground material etc.). However, there is still no clear consensus on where the optimum is and how to determine it (Hoogkamer, 2020). One reason for this may be that the combined effects of individual features are difficult to decompose (Burns & Tam, 2020). For example, even if only stack height is increased, the amount of material increases, and inevitably the mass also increases. Another challenge is the non-standardized measurement and reporting protocols both with respect to the shoes (e.g., measurement of the stack height or reporting the shoe features) and for study design (e.g., self-selected speed instead of a fixed one) that make the results difficult to compare (Frederick, 2020; Hannigan & Pollard, 2020).

Running style, defined as the "visually distinguishable movement pattern of a runner" (van Oeveren et al., 2021) was suggested to be important in terms of running performance as well as injuries (Barnes & Kilding, 2015; Floría et al., 2024; Folland et al., 2017; Mann et al., 2015; Nijs et al., 2022; Saunders et al., 2004). In a synthesis paper on the biomechanics of running and running styles, step frequency normalized to leg length (SF_{norm}) and duty factor (DF) were suggested to be sufficient to describe a running style (van Oeveren et al., 2021). Furthermore, they may help to interpret the running style in terms of performance. However, while spatiotemporal characteristics provide fundamental information on running style, they may still not be enough to understand it completely. For example, TenBroek et al. (2014) focused on various discrete joint angle variables and showed that running style changed when wearing shoes with different stack heights. In addition, a recent study showed that leg stiffness (k_{leg}) and vertical center of mass oscillation (COM_{osc}) contributed most to the variance to cluster the runners which underlined the distinguishing characteristic of these variables (Koegel et al., 2024). Additionally, a decreased COM_{osc} was associated with a better running economy (Folland et al., 2017). The studies focusing mainly on the effects of shoe stack height during running reported that a higher stack height may increase the effective leg length, therefore increase the step length as well as stance time (Burns & Tam, 2020; TenBroek et al., 2014); but a comprehensive analysis with respect to running style has not yet been conducted. Furthermore, while stiffness and center of mass (COM) movement changes due to different shoes have been analyzed in a few studies (Chambon et al., 2014; Kulmala et al., 2018), none focused on stack height,

especially on the higher height (i.e. ≥ 35 mm). Further data here may help to improve understanding of stack height effects. More concretely, Kulmala et al. (2018) compared two different running shoes which differed in multiple features, whereas Chambon et al. (2014) analyzed running shoes with stack heights only up to 16 mm. Consequently, there still exists a research gap in the study of higher stack heights in relation to running style.

In the context of running, stability can be defined as the ability to maintain functional running movement (e.g., without falls) despite the presence of perturbations (e.g., fatigue or different shoes (Frank et al., 2019; Schütte et al., 2018)). Stability during running is commonly discussed as it is crucial in terms of running performance as well as injuries (Barrons et al., 2023a; Bruijn et al., 2013; Frank et al., 2019; Hoenig et al., 2019; Promsri et al., 2024; Schütte et al., 2018) especially with respect to stack height (Barrons et al., 2023a; Esculier et al., 2015). In running studies, Maximum Lyapunov Exponent (MLE) has often been applied to operationalize the local dynamic stability of body regions or joint angles (Winter et al., 2024). It was shown that expertise level, running speed and fatigue affect local stability (Frank et al., 2019; Hoenig et al., 2019; Mehdizadeh et al., 2014). Another study on the effects of the shoe on stability showed that minimalist shoes did not differ from traditional shoes, but higher stack heights were not investigated (Frank et al., 2019). Another approach is to analyze the stability of a more global variable (i.e., stride interval) by looking into their long-range correlations using detrended fluctuation analysis (DFA) (Agresta et al., 2019; Hausdorff et al., 1996). The rationale behind this approach is that the inherent variability in gait data is not a random fluctuation but is a part of long-range power-law correlations. From a practical point of view, it means that the fluctuations in strides are related to variations in much earlier strides (Hausdorff et al., 1996). An increase in these long-range correlations (e.g., due to manipulations in footwear or foot strike patterns (Fuller et al., 2016)) is interpreted as a decreased ability to adapt running strides to a changed external condition, and therefore a reduced global stability (Agresta et al., 2019; Jordan et al., 2006).

Besides MLE and DFA, linear approaches have been used - particularly based on the movement of the ankle joint in the frontal plane. Thereby, discrete variables such as peak eversion/inversion foot angle or total eversion duration during stance are used to operationalize stability or to assess the risk of running-related injuries (Barrons et al., 2023a, 2024; Becker et al., 2017, 2018; Hannigan & Pollard, 2020; Isherwood et al., 2021; Kuhman et al., 2016; TenBroek et al., 2014). For example, Barrons and colleagues (2023a) reported a higher peak eversion angle for recreational runners with a higher stack height (45 mm vs. 35 mm), which was interpreted as a lower stability, but they did not investigate local dynamic stability. Since the studies mostly focus on one analysis level (e.g., either linear analysis (Law et al., 2019) or nonlinear analysis (Frank et al., 2019)), it becomes difficult to build a comprehensive understanding which combines results from different analysis approaches.

Addressing the above-mentioned research gaps, this study investigated the effects of shoes with different stack heights on running style and stability during level running at different speeds. It was hypothesized that the shoes with higher stack heights (≥ 35 mm) lead to changes in running style (H1) and reduced stability (H2). Additionally, it was expected that a higher running speed (i.e. 15 km/h) leads to more pronounced changes compared to a lower speed condition (i.e. 10 km/h) (H3).

2 Methods

2.1 Participants

Seventeen experienced healthy male runners participated in this study (age: 25.7 ± 3.9 years, height: 1.77 ± 0.04 m, mass: 68.1 ± 6.0 kg, shoe size: EU 42-43, running activity per week: 4.2 ± 1.8 days and

33.7 ± 22.4 km). All participants provided written informed consent prior to the measurements. The study was approved by the ethics committee of the Karlsruhe Institute of Technology (KIT).

2.2 Experimental protocol

The measurements were conducted on a treadmill (h/p/cosmos Saturn, Nussdorf-Traunstein, Germany). The experimental protocol began with a warm-up and familiarization to the treadmill and three slope conditions (0%, -10% and 10%) by running at self-selected speed with their own shoes for 5 minutes in total (Paquette et al., 2024). This study focuses only on the 0% condition. Then, the measurement blocks were repeated for three running shoes with different stack heights tested in this study (**H**igh: 50 mm, **M**edium: 35 mm and **L**ow: 27 mm, measured at the rearfoot) in a parallelized order (Table 1). H and M included advanced footwear technology elements but L did not. For each shoe condition, the protocol began with a familiarization to the current shoes by running at self-selected speed for 3 minutes and walking at 5 km/h for 2 minutes in the level condition (0%) (Paquette et al., 2024). Afterwards, a total of six running trials with different slope and speed conditions were performed. For each slope condition, first the slow than the fast running condition was performed. For the 0% condition, 10 km/h and 15 km/h were chosen based on the test measurements and previous studies (Fadillioglu et al., 2022; Kulmala et al., 2018; Selvakumar et al., 2023). Each of the six running trials lasted 90 s. Before each trial the participants ran for 25-40 s until the treadmill reached the target speed. There were 1 min walking breaks between the slow and fast running conditions and a 2 min standing break between the slope conditions to prevent exhaustion. A Borg scale (Borg, 1998) was used before each running trial to control the exhaustion level (i.e. the next trial did not begin unless the Borg score was <12 on a 6-20 scale). After each pair of shoes, a visual analogue scaled comfort questionnaire for the stability, cushioning and comfort in a range of 0-100% (from low to high) was collected (Fadillioglu et al., 2024).

2.3 Data acquisition, data processing and biomechanical modelling

A 3D motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK; 200 Hz) with 65 reflective markers was used to capture full body kinematics. Raw kinematic data were processed offline with Vicon Nexus V2.12 to reconstruct the 3D coordinates of the markers. Further data processing was performed in MATLAB (2023a, MathWorks Inc., Natick, USA). Marker data were filtered using a low pass Butterworth filter (4th order, cut-off frequency 10 Hz (Gullstrand et al., 2009)). A full-body model (modified version of the OpenSim Hamner Running Model (Delp et al., 2007; Hamner et al., 2010)) was used to calculate joint kinematics using the OpenSim. The model was iteratively scaled for each subject separately until the maximum marker error was less than 2 cm and the root mean square error less than 1 cm. The weights for all markers were equal. The initial contact events were detected based on the local minimum in velocity curves of the mean of heel and toe markers (Leitch et al., 2011) and the toe-off events based on the maximum extension in sagittal knee angles (Fellin et al., 2010). The parameters for linear and nonlinear analyses were determined for 20 and 100 running strides, respectively, of the left side (Ogaya et al., 2021; Riazati et al., 2019). For the linear analysis, the 20 strides were selected from the first ~15-35% of the 90 s recording period to minimize the number of missing markers during labelling of data, as some markers fell off due to the dynamic characteristic of running or sweating towards the end of the trials. For the nonlinear analysis, the 100 strides were selected from the ~5-85% of the 90 s recording period.

2.4 Data analysis

2.4.1 Running style

The SF_{norm} was calculated based on initial contacts, and normalized to leg length (l_0) (Eq. 1) (Hof, 1996; van Oeveren et al. 2021).

$$SF_{norm} = \frac{SF}{\sqrt{\frac{g}{l_0}}} \quad \text{Eq. 1}$$

The DF was calculated as the ratio of stance time to the twice the sum of stance and flight time (Eq. 2) (Fadillioglu et al., 2022; van Oeveren et al., 2021).

$$DF = \frac{t_{stance}}{2\left(t_{stance} + t_{flight}\right)} \quad \text{Eq. 2}$$

The results of SF_{norm} and DF are based on the dual-axis framework for running style (van Oeveren et al., 2021).

The landing and take-off timings during stance were estimated using the maximum knee flexion event (Ciacci et al., 2010). The ratio of landing to take-off duration (L2T) was calculated (Eq. 3) to estimate the landing-take-off asymmetries (da Rosa et al., 2019).

$$L2T = \frac{t_{landing}}{t_{takeoff}} \quad \text{Eq. 3}$$

Frontal and sagittal angle time series of the ankle, knee and hip joints were time-normalized to stance phase (101 points) for each cycle separately using a cubic spline interpolation (Möhler et al., 2022). The individual time series were compared with each other across different shoe and speed conditions.

COM_{osc} was calculated for the stance phase by the range of motion of COM in vertical direction. Vertical stiffness (k_{ver}) and leg stiffness (k_{leg}) were estimated using Eq. 4 and Eq. 5, respectively (Garofolini et al., 2022; Morin et al., 2005).

$$k_{ver} = \frac{m\,g\,\frac{\pi}{2}\left(\frac{t_{flight}}{t_{stance}} + 1\right)}{COMosc} \quad \text{Eq. 4}$$

$$k_{leg} = \frac{m\,g\,\frac{\pi}{2}\left(\frac{t_{flight}}{t_{stance}} + 1\right)}{l_0 - \sqrt{{l_0}^2 - \left(\frac{v\,t_{stance}}{2}\right)^2} + \ COMosc} \quad \text{Eq. 5}$$

2.4.2 Running stability

In the linear analysis, the following were calculated: total time at eversion normalized to stance time ($t_{eversion}$), maximum eversion ($MAX_{eversion}$) and maximum inversion ($MAX_{inversion}$) angles during stance phase, and ankle frontal angle at initial contact ($IC_{inversion}$) (Barrons et al., 2023a, 2024; Hannigan & Pollard, 2020; Isherwood et al., 2021; TenBroek et al., 2014).

In the nonlinear analysis, the local dynamic stability of foot, hip, trunk and head in the vertical axis were determined using MLE of marker clusters (each consisting of four markers) attached to the corresponding body regions (Ekizos et al., 2018; Hunter et al., 2023; Jordan et al., 2009; Look et al., 2013; Winter et al., 2024). Time series data of 100 strides were normalized to 10,000 points (100 strides x 100 points) (Hoenig et al., 2019a; Raffalt et al., 2019). Embedding dimension (*m*) was

determined based on the false nearest neighbor method for all trials (Stergiou, 2016; Wallot & Mønster, 2018). The largest *m* over all trials was used for each region (m_{foot} = 10, m_{hip} = 8, m_{trunk} = 10, m_{head} = 8) (Hoenig et al., 2019a). Time lag (τ) for the reconstruction of the space was determined based on the first local minimum of the average mutual information curves (Stergiou, 2016; Wallot & Mønster, 2018). The median τ over all trials for each body region was used for further calculations (τ_{foot} = 26, τ_{hip} = 23, τ_{trunk} = 23, τ_{head} = 23) (Hoenig et al., 2019a). Rosenstein's algorithm was used to estimate the divergence curve (Eq. 6) (Ekizos et al., 2017; Rosenstein et al., 1993). The slope of short-term phase (λ) was used to calculate MLE (Mehdizadeh et al., 2014). A lower λ indicated a higher dynamic local stability, and vice versa.

$$\mathrm{S(t)} = [z(t), z(t+\tau), \dots, z(t+(m-1)\,\tau)\,] \qquad \text{Eq. 6}$$

A DFA of stride time was performed to assess long-range correlations of running stride (Hunter et al., 2023; Jordan & Newell, 2008; Mann et al., 2015). First, the data series x was shifted by its average, summed cumulatively to obtained the integrated data (Eq. 7) and segmented into non-overlapping windows with a size of Δn varying between 4 and 24 time points. In the second step, integrated data were locally fit to a line by the least square method in each window, and average fluctuation of the time series around the estimated trend was calculated (Eq. 8). The second step was repeated for all the window sizes Δn (Bryce & Sprague, 2012).

$$A(w) = \sum_{i=1}^{w} (x(i) - x_{avg}) \qquad \text{Eq. 7}$$

$$F(\Delta\mathrm{n}) = \sqrt{\frac{1}{N} \sum_{w=1}^{N} (A(w) - A_{\Delta\mathrm{n}}(w))^2} \qquad \text{Eq. 8}$$

If the data show power law scaling characteristics, then a logarithmic (i.e., log-log) plot of F(Δn) vs. Δn is expected to be linear (Eq. 9). The slope of this curve gives the scaling component DFA-α which is used to quantify the long-range correlations of data. If the DFA-α lies between 0.5 and 1, the data show a self-similarity characteristic (e.g., a short stride is more likely to follow a short stride). In this range, the larger the DFA-α, the higher the persistence of data, which is interpreted as reduced stability (Agresta et al., 2019; Jordan et al., 2009).

$$\mathrm{F}\,(\Delta\mathrm{n}) \;\propto\; (\Delta\mathrm{n})^{\mathrm{DFA}-\alpha} \qquad \text{Eq. 9}$$

2.5 Statistics

2.5.1 Running style

The statistical tests for discrete parameters were performed in SPSS (Version 29.0, SPSS Inc., IBM, Armonk, NY, USA). The average of the 20 cycles in each running trial was calculated for comparisons. The normality and sphericity were checked by the Kolmogorov-Smilnov and Mauchly tests, respectively. Greenhouse-Geisser estimates were used to correct for violations of sphericity. Repeated measurements analyses of variance (rmANOVAs) were performed to compare conditions

where the independent factors were the shoe (H, M, L) and speed (10 km/h, 15 km/h). Eta squared (η^2) was calculated to estimate the sizes of the main effects (small $\eta^2 \leq 0.06$; medium $0.06 < \eta^2 < 0.14$; large $0.14 \leq \eta^2$). Paired t-tests with Bonferroni-Holm corrections were calculated as *post-hoc* tests. In the case of a global shoe effect, the mean data at 10 km/h and 15 km/h were used in *post-hoc* tests, whereas in the case of a significant interaction effect, the *post-hoc* tests were performed for 10 km/h and 15 km/h separately. Cohen's d was calculated to estimate the effect sizes for *post-hoc* tests (small $d \leq 0.50$; medium $0.50 < d < 0.80$; large $0.80 \leq d$) (Cohen, 1988). The significance level was set *a priori* to $\alpha = 0.05$.

The angle time series within each joint dimension were compared using the statistical parametric mapping (SPM) toolbox in MATLAB (spm1d toolbox) (Pataky et al., 2019). Normality was checked using the normality tests provided in the toolbox. In the case of non-normality, nonparametric alternatives were conducted with 1,000 iterations. In the case of significant effects, the paired t-tests were calculated as *post-hoc* tests. The significance level was set *a priori* to $\alpha = 0.05$.

2.5.2 Running stability

The statistical tests were also performed in SPSS. For the comparisons of linear analysis, the average of the 20 cycles in each running trial was calculated. Within the nonlinear analysis, a single value was obtained for 100 cycles of each running trial. The Kolmogorov-Smilnov and Mauchly tests were used to check the normality and sphericity, respectively. rmANOVAs were performed to compare conditions with the independent factors shoe (H, M, L) and speed (10 km/h, 15 km/h). In the case of a global shoe effect, paired t-tests with Bonferroni-Holm corrections were performed as *post-hoc* tests in which the mean data of 10 km/h and 15 km/h were used to compare shoe conditions independent of the speed effects. η^2 and d were calculated to estimate the effects sizes as explained above. The significance level was set *a priori* to $\alpha = 0.05$.

3 Results

3.1 Running style

The discrete parameters used for running style analysis are represented in Table 2. Fig. 1 visualizes the results for SF_{norm} and DF in the dual-axis framework. The SF_{norm} showed significant interaction between shoes and speed ($p = 0.001$). Furthermore, it was significantly higher at 15 km/h compared to 10 km/h ($p < 0.001$). The *post-hoc* analysis showed that the SF_{norm} of L was significantly higher than H ($p = 0.046$) and M ($p = 0.012$) and H was higher than M ($p = 0.038$) at 15 km/h.

The DF was significantly different between shoes ($p = 0.018$). Additionally, the DF was significantly lower at 15 km/h compared to 10 km/h ($p < 0.001$). According to the *post-hoc* analysis, the DF was higher for H compared to L independent of speed ($p = 0.021$). The L2T showed no significant effects (Table 2).

The ankle, knee and hip joint time series are shown in Fig. 2 and Fig. 3 for the sagittal and frontal planes, respectively. The SPM analysis revealed significant shoe effects for the sagittal and frontal ankle angles. The hip and knee angles did not differ significantly between the shoes. All joint angles differed significantly between 10 km/h and 15 km/h in both planes (sagittal: ankle, $p = 0.032$; knee, $p = 0.001$, hip, $p = 0.001$; frontal: ankle, $p = 0.001$; knee, $p = 0.001$, hip, $p = 0.001$). No interaction effects were detected. *Post-hoc* SPM t-tests revealed that M led to significantly higher inversion compared to H and L (both $p < 0.001$). *Post-hoc* results in the sagittal plane did not reach the significance level.

The COM_{osc}, k_{ver} and k_{leg} results are shown in Table 2 and Fig. 4. The COM_{osc} differed significantly between the shoes ($p = 0.013$) and was significantly lower at 15 km/h compared to 10 km/h (p =

0.001). The *post-hoc* tests revealed that all pairwise comparisons between shoes were significant (Table 2). The k_{ver} showed significant shoe effects ($p = 0.014$) and was higher at 15 km/h compared to 10 km/h ($p < 0.001$). The *post-hoc* tests revealed significant differences between all shoes. The k_{leg} was significantly lower at 15 km/h compared with 10 km/h ($p < 0.001$).

To sum up, at 15 km/h but not at 10 km/h, the shoes with the medium stack height (M) resulted in higher SF_{norm} compared to other stack heights (H & L). In addition, the highest stack height shoes led to a higher DF compared with the lowest, independent of running speed. Ankle angle time series in the sagittal and frontal planes revealed significant differences between shoes independent of the speed. Finally, COM_{osc} increased with increasing stack height, k_{ver} decreased and k_{leg} was not affected by the shoes.

3.2 Running stability

3.2.1 Linear analysis

The results are summarized in Table 3. The $t_{eversion}$ differed between the shoes ($p = 0.035$). The *post-hoc* tests revealed that M spent less time in eversion compared with H ($p = 0.006$) and L ($p = 0.046$) independent of the running speed (Table 3). $MAX_{eversion}$ showed significant effects for shoes only ($p = 0.006$). The *post-hoc* tests showed that $MAX_{eversion}$ during stance was lower in M compared to both H ($p = 0.002$) and L ($p = 0.010$). The results of $MAX_{inversion}$ showed significant differences for both shoe ($p = 0.005$) and speed ($p < 0.001$). According to the *post-hoc* tests, the $MAX_{inversion}$ during stance was lower (higher in amount) in M compared to both H ($p = 0.002$) and L ($p = 0.004$). The $IC_{inversion}$ showed significant differences only for the factor speed ($p = 0.001$).

To sum up, the linear analysis of stability showed that (1) the shoes with the medium stack height (M) shifted the frontal ankle angle less eversion compared to the highest (H) and lowest stack height (L); and (2) the highest (H) and lowest stack height (L) shoes led to a longer duration in an everted foot position than the medium stack height (M).

3.2.2 Nonlinear analysis

The results are summarized in Table 4. The λ_{hip} showed significant effects for the factor shoe ($p = 0.040$). The *post-hoc* results showed a reduced local stability in the hip for H compared to L ($p = 0.027$). Head, trunk and foot did not show significant effects. The DFA-α was higher at 15 km/h compared to 10 km/h ($p < 0.001$).

To sum up, the local stability of the hip was lower in the shoes with the highest stack height (H) compared with the lowest stack height (L); but head, trunk and foot did not differ between the shoes. The DFA-α of stride time did not show any significant differences between shoes.

4 Discussion

This study aimed to understand the effects of different shoe stack heights on running style and stability during treadmill running at two different speeds. The results showed that the higher stack heights can affect running style (i.e. SF_{norm}, DF, COM_{osc}, k_{ver}, sagittal and frontal ankle angles) and reduce stability (i.e. $t_{eversion}$ $MAX_{eversion}$, $MAX_{inversion}$ and $\boldsymbol{\lambda_{hip}}$), in line with H1 and H2. The findings were not speed dependent but global effects, which contradicts H3.

4.1 Higher shoe stack height leads to changes in running style parameters that are associated with a decreased running economy

Running style is important for economy and performance (Folland et al., 2017). It was hypothesized here that different shoe stack heights modulate the running style (H1). This study revealed that, at a

greater speed, the higher stack heights (H and M) led to a lower SF_{norm} compared to the lowest stack height (L). This can be interpreted as a shift of the running style to the direction of the "push" style associated with longer steps (van Oeveren et al., 2021). In addition, independent of running speed, the highest stack height led to higher DF compared with the lowest stack height, which can be interpreted as a running style shifted to the direction of a "stick" style associated with longer stance time relative to stride time (van Oeveren et al., 2021). When it comes to the ratio of landing to takeoff (i.e. L2T), the results showed that the landing had a shorter duration than the takeoff, but L2T remained unaffected by different shoes and running speeds. To sum up, the highest stack height (H) altered the running style to longer steps with longer ground contacts relative to the stride time, especially compared to the lowest stack height (L) and faster speed.

Further analysis revealed that COM_{osc} increased with increasing stack height, but k_{ver} decreased since it is inversely proportional to COM_{osc} (Eq. 4). This finding may be interpreted as decreased running economy for the highest stack height condition, since a larger COM_{osc} is associated with worse running economy (Folland et al., 2017; Saunders et al., 2004).

The results of k_{leg} showed significant speed effects but no shoe effects. This secondary finding is surprising since k_{leg} takes effective leg length into account, thereby eliminating the speed dependency; unlike k_{ver} which increases with running speed. Normally, it is expected that k_{leg} remains relatively stable across different running speeds (Brughelli & Cronin, 2008) which was not the case in the current study. Possibly, it is because the stiffness parameters were estimated based on kinematics without any force measurements, therefore possibly they are less reliable compared to measures based on kinetics. However, the kinematics-based method has also been used in various other studies to estimate stiffness (e.g., Burns et al., 2021; Morin et al., 2005).

Finally, the analysis of joint angle time series of the lower limb showed that the different stack heights affect joint kinematics to a certain extent. In the frontal plane, the middle stack height shoes led to a decreased frontal ankle angle (shift to inversion) compared to other shoes, whereas in the sagittal plane there were no significant effects in the *post-hoc* tests. These results indicated that the different shoe stack heights affect mainly the ankle but not the more proximal joints of the lower body (i.e. the knee and hip).

Based on these findings related to the running style, it may be suggested that the different shoe stack heights lead to some changes in running style, in parallel with H1. In particular, the highest stack height resulted in changes to parameters associated with a decreased running economy (Folland et al., 2017; Saunders et al., 2004). It can be speculated that 50 mm stack height may lead to a less economical running style. This contradicts the findings that the higher stack heights can increase running economy due to increased effective leg length (Burns & Tam, 2020). Nevertheless, it should be noted that running economy was not directly measured therefore this is not necessarily true. For example, Fletcher et al. (2008) detected differences in COM_{osc} but not in running economy. Therefore, the findings should be interpreted with caution.

4.2 Reduced running stability with highest stack height

In this study, it was hypothesized that the shoes with higher stack heights lead to less stability (H2), in line with previous findings (Hoogkamer, 2020; Ruiz-Alias, Jaén-Carrillo, et al., 2023). Both linear and nonlinear analyses were carried out in a comprehensive approach. Linear measures provide essential information such as mean and standard deviation on the analyzed parameters but they assume that the output of the system is directly proportional to the input although biological systems are inherently nonlinear (McCamley & Harrison, 2016). Therefore, nonlinear analysis complements linear analysis by providing deeper insights to biological systems without simple linearity assumptions. The linear analysis of joint angles based on discrete parameters revealed that the shoes

with the middle stack height led to a lower $MAX_{inversion}$ and $MAX_{eversion}$ during stance. It is important to note that $MAX_{eversion}$ values were partially still in the region of an inversion (Fig. 3). Together with the joint angle time series data, it can be concluded that the middle stack height shifted the frontal ankle angle to a more inverted position compared to the highest and lowest stack height. The $t_{eversion}$ results revealed that the highest stack height led to a longer duration in an everted foot position compared to the middle stack, which may be indicator for a decreased stability (Becker et al., 2018; Hannigan & Pollard, 2020). However, it should be noted that the shoes with the highest stack were not less stable compared to the lowest stack height shoes. This may be attributed to the missing advanced footwear technology elements in the. Possibly, the advanced footwear technology (e.g., stiffening elements) elements help to increase ankle stability but extremely high stack heights (i.e. 50 mm) counterbalance the advantages of these technologies. Thereby, the linear analysis results partially supported H2. These findings were in line with those from Barrons et al. (2023a) but not fully matched them. In their study, the shoes with 35 mm stack height decreased ankle eversion compared with 45 mm, whereas the comparison between 35 mm and 50 mm did not reach the significance level at *post-hoc* even though their tendency was the same. Furthermore, they reported that the reduced stability with 45 mm shoes compared to 35 mm did not translate into a reduced running economy. It should also be noted that the frontal ankle angle values were slightly different from those in this study, even though the tendencies due to different shoes were similar. These differences were probably due to different marker sets and inverse kinematics models used. Previous studies reported that the kinematics results may change, especially in the non-sagittal planes, when different setups are used for gait analysis (Roelker et al., 2017; Trinler et al., 2019; Wouda et al., 2018). Nevertheless, Barrons et al. (2023a).

The nonlinear analysis indicated that local stability of the hip based on MLE was lower with the highest stack height compared to the lowest one. In this context, hip stability can be seen as the most important location since the fundamental goal of locomotion is to transport the COM (Evans et al., 2022) and the hip can be used to approximate the COM during running (Napier et al., 2020). The MLE results indicated that stabilization of the hip became more difficult with the highest stack height compared to the lowest, which thereby supported H2. The DFA of stride time indicated a self-similarity characteristic (e.g., a short stride is more likely to follow a short stride). In contrast to MLE, the DFA of stride time did not show any significant shoe differences, which was against H2. One explanation may be that the shoes provide only small perturbations for the system (Prejean & Ricard, 2019).

In this study, one of the goals was to operationalize stability from different perspectives to gain a better understanding of stack height effects on stability. First, the discrete frontal ankle angles indicated a higher portion of eversion during stance for the highest stack compared to middle high. Secondly, the local dynamic stability of the hip during running was lower with the highest stack height compared to the lowest one. These results are in line with the perceived stability results of the data used in this study (Fadillioglu et al., 2024) as well as with previous studies suggesting that increasing stack height may lead to instabilities (Hoogkamer, 2020; Ruiz-Alias et al., 2023a). Based on these findings, it can be suggested that high stack height (i.e. 50 mm) lead to instabilities in frontal ankle angle and hip local stability, but it should be noted that not all parameters supported this statement. For example, the local dynamic stability of the foot did not change. Nevertheless, this is not in conflict with the frontal ankle angle results since linear and nonlinear analyses do not have the same assumptions (McCamley & Harrison, 2016).

4.3 Stack height changes were largely independent of running speed

In general, higher running speeds may represent more challenging task conditions than lower speeds (Santuz et al. 2020), thereby increase the influence of stack heights. In this study, it was hypothesized that the effects of different stack heights would be pronounced at higher speeds (H3).

The detected shoe effects did not change between the two running speeds, and only SF_{norm} had significant interaction effect between the factors speed and shoe. More concretely, the shoe effects were visible at a higher speed only for SF_{norm}. Based on these findings, it can be suggested that the detected shoe effects were mostly global effects, which means that they were independent of the tested running speeds, with the exception of the running style parameter SF_{norm}. Therefore, H3 should be rejected with the exception of the SF_{norm}.

As a secondary finding, it was indirectly shown that the tested higher speed was probably more challenging the tested lower speed by DFA-α. More concretely, the DFA-α of stride time shows a U-shaped structure with increasing speed where the DFA-α reaches it minimum at a preferred speed (Jordan et al., 2007, 2009). In the current study, the DFA-α at 10 km/h was significantly lower than at 15 km/h, indicating that 10 km/h was closer to the preferred speed than 15 km/h. In other words, 15 km/h was less preferred, and probably more challenging for the runners.

4.4 Limitations

This study has some limitations that must be mentioned. Firstly, the shoes differed mainly in their stack heights but not all the remaining shoe features were identical. For example, the weight of the shoes slightly differed but the difference between the lightest and heaviest ones was only 49 g (Table 1). It has previously been shown that an added mass of 50 g resulted in limited biomechanical changes (Rodrigo-Carranza et al., 2020). Furthermore, the shoes with the highest and middle high stack height included advanced footwear technology elements but the lowest stack height shoes had not. Secondly, the experiments were done on a treadmill at two constant running speeds. Even if it is done in a similar way in many comparable studies also (e.g., Barrons et al., 2023a; Chambon et al., 2014; Udin et al., 2023), it should be kept in mind that this is a very controlled experimental condition. It is possible that larger additional perturbations to the system (e.g., higher running speed, uneven ground and fatigue) will increase the shoe effects. Lastly, the participants were healthy experienced runners and the findings cannot be directly translated to other expertise levels (Fadillioglu et al., 2022; Möhler et al., 2020).

5 Conclusion

The purpose of this study was to investigate how three shoes with different stack heights affect running style and stability during treadmill running at different speeds. The key findings of this study were: (1) changes in stack height can affect running style. Particularly, the shoes with the highest stack height resulted in longer steps with longer ground contacts relative to the stride time and higher vertical oscillation of the COM compared to the lowest stack. (2) The ankle spent longer in an everted position with the highest stack compared to the middle heigh. In addition, the local dynamic stability of the hip during running was lower with the highest stack compared to the lowest one. Both results indicated that the highest stack height (50 mm) reduce stability. Nevertheless, based on the findings of Barrons et al. (2023a), it may be suggested that this reduced stability probably does not translate into a reduced economy. Furthermore, not all stability parameters indicated decreased stability for the highest stack height. (3) The higher stack heights (≥ 35 mm) led to a lower step frequency normalized to leg length at 15 km/h but not at 10 km/h. The remaining shoe effects were independent of the running speed.

Shoe stack height is a highly discussed topic especially since the introduction of a stack height regulation by World Athletics (Barrons et al., 2023b; Hoogkamer, 2020; Ruiz-Alias, Jaén-Carrillo, et al., 2023; Ruiz-Alias, Pérez-Castilla, et al., 2023; Willwacher & Weir, 2023). The findings of the study are in line with the statement “more is not always better” when it comes to the stack height (Hoogkamer, 2020). This study has found another piece of puzzle in understanding the effects of stack heights on running style and stability. Future studies may focus on running coordination (Garofolini et al., 2024) as well as analysis of joint loads (Richert et al., 2019) and muscle activities (Santuz et al. 2020) to better understand stack height effects.

Acknowledgements

We acknowledge support by the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Funding information

Adidas AG provided financial and material support for this study. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethics statements

Studies involving animal subjects

No animal studies are presented in this manuscript.

Studies involving human subjects

The studies involving humans were approved by the ethics committee of the Karlsruhe Institute of Technology (KIT). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Inclusion of identifiable human data

No potentially identifiable images or data are presented in this study.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Generative AI disclosure

No Generative AI was used in the preparation of this manuscript.

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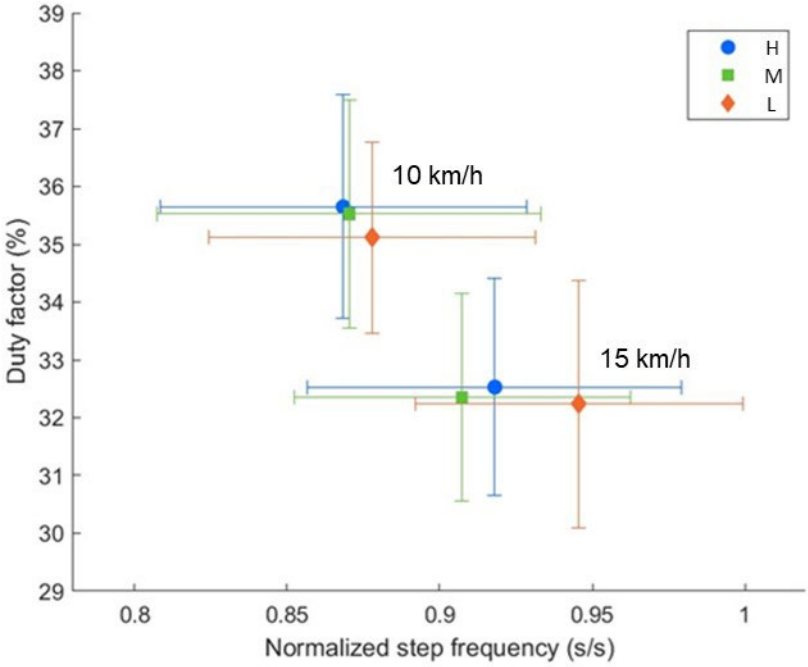

Figure 1: Running style analysis based on the dual-axis framework (van Oeveren et al., 2021) for different shoes (stack height, H: 50 mm, M: 35 mm & L: 27 mm) and running speeds (10 km/h and 15 km/h). The symbols indicate the mean values of each shoe and the error bars show standard deviations.

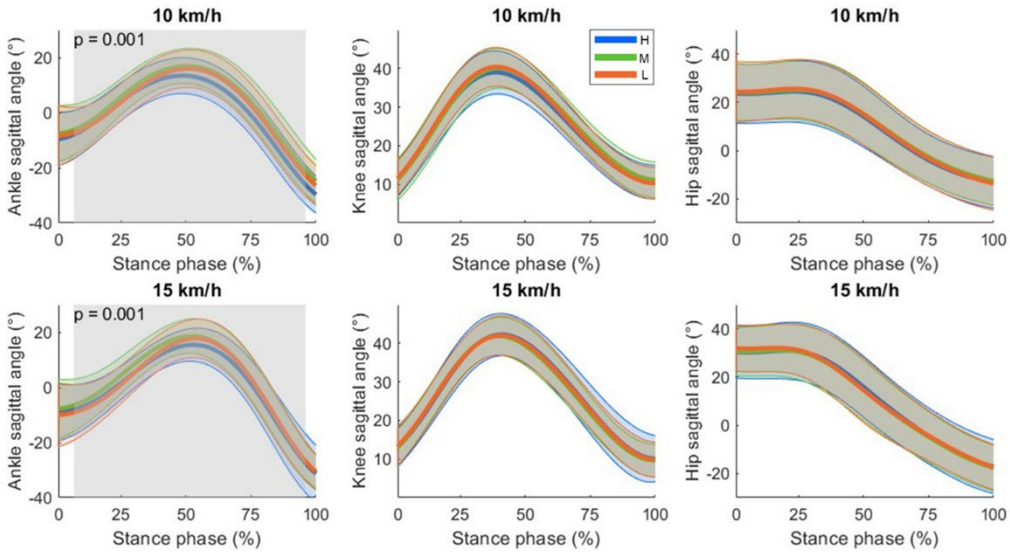

Figure 2: Sagittal plane joint angle time series for ankle, knee and hip as mean (thicker lines) ± standard deviations (upper and lower thinner lines). By convention, a positive angle indicated a flexion for all the joints (dorsiflexion in case of the ankle). Significant shoe differences independent of the running speed are highlighted with shaded areas. The corresponding p-values are also displayed. Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm.

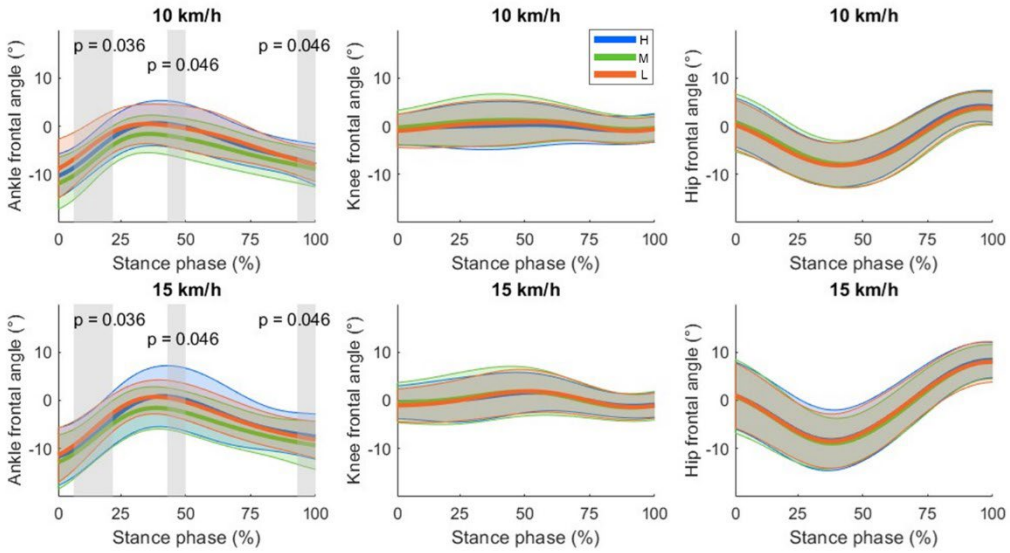

Figure 3: Frontal plane joint angle time series for ankle, knee and hip as mean (thicker lines) ± standard deviations (upper and lower thinner lines). By convention, a positive angle indicated an abduction for the knee and hip, and an eversion for the ankle. Significant shoe differences independent of the running speed are highlighted with shaded areas. The corresponding p-values are also displayed. Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm.

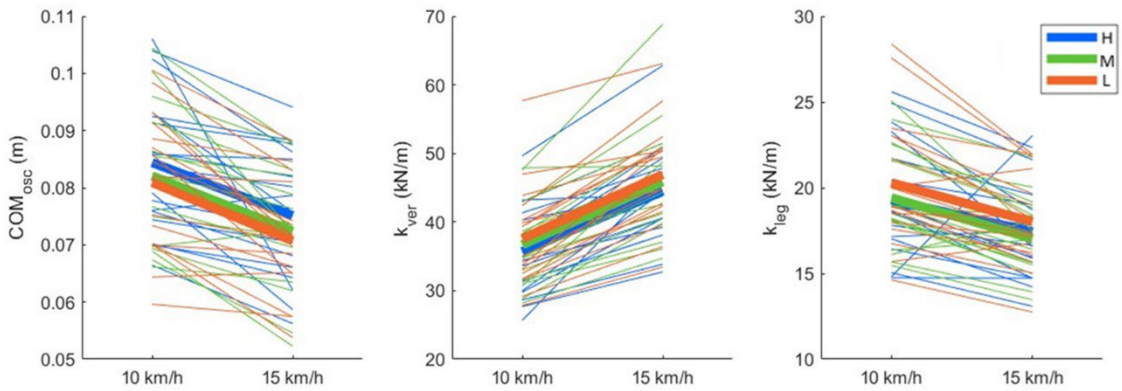

Figure 4: Vertical oscillation of the center of mass (COM_{osc}), vertical stiffness (k_{ver}) and leg stiffness (k_{leg}) results. Thicker lines show mean values for each shoe, whereas thinner lines show each participant separately. Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm.

Table 1: Features of the tested running shoes.

Shoe	Mass (g)	Forefoot height (mm)	Rearfoot height (mm)	Heel-to-toe drop (mm)
High	268	43 mm	50 mm	7 mm
Medium	220	28 mm	35 mm	7 mm
Low	219	19 mm	27 mm	8 mm

Table 2: The discrete parameters used for running style analysis: step frequency normalized to leg length (SF_{norm}), duty factor (DF), ratio of landing to take-off duration (L2T), vertical center of mass oscillation (COM_{osc}), vertical stiffnes (k_{ver}) and leg stiffness (k_{leg}). Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm. Descriptive statistics is given as mean ± standard deviation. Unless otherwise specified, the *post-hoc* results were calculated for mean data at 10 km/h and 15 km/h. Significant results are highlighted in bold.

SF_{norm} (s/s)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc 10 km/h*	p	|d|
H	0.87 ± 0.06	0.92 ± 0.06	Shoe	0.112	0.146	H vs. M	0.342	0.10
M	0.87 ± 0.06	0.90 ± 0.05	Speed	**<0.001**	**0.727**	H vs. L	0.735	0.17
L	0.88 ± 0.05	0.94 ± 0.05	Interaction	**0.001**	**0.348**	M vs. L	0.576	0.14
						Post-hoc 15 km/h	p	|d|
						H vs. M	**0.038**	**0.46**
						H vs. L	**0.046**	**0.53**
						M vs. L	**0.012**	**0.73**
DF (%)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	0.36 ± 0.02	0.32 ± 0.02	Shoe	**0.018**	**0.222**	H vs. M	0.176	0.23
M	0.35 ± 0.02	0.32 ± 0.02	Speed	**<0.001**	**0.862**	H vs. L	**0.021**	**0.67**
L	0.35 ± 0.01	0.32 ± 0.02	Interaction	0.510	0.041	M vs. L	0.144	0.37
L2T (s/s)								
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	0.64 ± 0.06	0.67 ± 0.05	Shoe	0.952	0.003			
M	0.64 ± 0.05	0.67 ± 0.04	Speed	0.107	0.164			
L	0.64 ± 0.06	0.66 ± 0.07	Interaction	0.494	0.046			
COM_{osc} (m)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	0.084 ± 0.012	0.075 ± 0.011	Shoe	**0.013**	**0.287**	H vs. M	**0.035**	**0.47**
M	0.082 ± 0.012	0.072 ± 0.010	Speed	**0.001**	**0.698**	H vs. L	**0.012**	**0.74**
L	0.081 ± 0.011	0.070 ± 0.001	Interaction	0.925	0.005	M vs. L	**0.030**	**0.58**
k_{ver} (kN/m)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	35.66 ± 6.48	44.53 ± 7.15	Shoe	**0.014**	**0.282**	H vs. M	0.060	0.40
M	36.69 ± 6.01	45.86 ± 8.26	Speed	**<0.001**	**0.886**	H vs. L	**0.009**	**0.75**
L	37.57 ± 7.45	46.92 ± 7.45	Interaction	0.938	0.004	M vs. L	**0.010**	**0.71**
k_{leg} (kN/m)								
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	19.29 ± 3.49	17.42 ± 2.95	Shoe	0.154	0.110			
M	19.41 ± 2.96	17.03 ± 2.26	Speed	**<0.001**	**0.576**			
L	20.28 ± 3.82	18.01 ± 2.63	Interaction	0.719	0.020			

Table 3: The parameters used in the linear analysis of running stability: total time at eversion normalized to stance time ($t_{eversion}$), maximum eversion ($MAX_{eversion}$) and maximum inversion ($MAX_{inversion}$) angles during stance phase, and ankle frontal angle at initial contact ($IC_{inversion}$). Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm. Descriptive statistics is given as mean ± standard deviation. The *post-hoc* tests were calculated for mean data at 10 km/h and 15 km/h. Significant results are highlighted in bold.

$t_{eversion}$ (%)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	21.5 ± 27.2	24.8 ± 27.2	Shoe	**0.035**	**0.189**	H vs. M	**0.006**	**0.83**
M	13.2 ± 21.7	14.2 ± 22.1	Speed	0.504	0.028	H vs. L	0.371	0.08
L	22.1 ± 26.7	21.2 ± 21.0	Interaction	0.423	0.052	M vs. L	**0.046**	**0.52**
$MAX_{eversion}$ (°)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	1.0 ± 4.7	1.6 ± 6.0	Shoe	**0.006**	**0.271**	H vs. M	**0.002**	**0.92**
M	-1.3 ± 4.0	-1.1 ± 4.5	Speed	0.332	0.059	H vs. L	0.388	0.07
L	0.8 ± 4.1	1.2 ± 3.7	Interaction	0.859	0.009	M vs. L	**0.010**	**0.71**
$MAX_{inversion}$ (°)								
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	-10.9 ± 4.5	-12.9 ± 5.5	Shoe	**0.005**	**0.284**	H vs. M	**0.002**	**0.90**
M	-12.5 ± 4.8	-13.8 ± 5.3	Speed	**<0.001**	**0.555**	H vs. L	0.430	0.04
L	-10.8 ± 3.5	-12.9 ± 4.9	Interaction	0.583	0.033	M vs. L	**0.004**	**0.85**
$IC_{inversion}$ (°)								
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	-10.3 ± 4.6	-11.7 ± 6.0	Shoe	0.057	0.192			
M	-11.8 ± 5.4	-12.8 ± 5.6	Speed	**0.001**	**0.480**			
L	-8.8 ± 6.2	-11.3 ± 5.7	Interaction	0.477	0.045			

Table 4: The parameters used in the nonlinear analysis of running stability: local dynamic stability of head (λ_{head}), trunk (λ_{trunk}), hip (λ_{hip}) & foot (λ_{foot}); detrended fluctuation scaling component of stride time (DFA-α). Shoe stack heights were abbreviated as H: 50 mm, M: 35 mm & L: 27 mm. Descriptive statistics is given as mean ± standard deviation. The *post-hoc* tests were calculated for mean data at 10 km/h and 15 km/h. Significant results are highlighted in bold.

			λ_{head}					
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	1.52 ± 0.12	1.52 ± 0.14	Shoe	0.605	0.017			
M	1.53 ± 0.16	1.51 ± 0.11	Speed	0.423	0.052			
L	1.50 ± 0.14	1.48 ± 0.11	Interaction	0.903	0.006			
			λ_{trunk}					
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	1.11 ± 0.07	1.10 ± 0.13	Shoe	0.123	0.201			
M	1.12 ± 0.14	1.12 ± 0.08	Speed	0.233	0.859			
L	1.11 ± 0.10	1.04 ± 0.12	Interaction	0.124	0.610			
			λ_{hip}					
	10 km/h	15 km/h	rmANOVA	p	η^2	*Post-hoc*	p	|d|
H	1.48 ± 0.13	1.43 ± 0.15	Shoe	0.253	0.081	H vs. M	0.241	0.17
M	1.46 ± 0.16	1.41 ± 0.14	Speed	**0.040**	**0.182**	H vs. L	**0.027**	**0.64**
L	1.38 ± 0.14	1.39 ± 0.01	Interaction	0.373	0.060	M vs. L	0.115	0.40
			λ_{foot}					
	10 km/h	15 km/h	rmANOVA	p	η^2			
H	1.05 ± 0.12	1.06 ± 0.10	Shoe	0.201	0.100			
M	1.01 ± 0.16	1.08 ± 0.13	Speed	0.859	0.009			
L	1.03 ± 0.13	1.08 ± 0.16	Interaction	0.610	0.030			
			DFA-α					
	10 km/h	15 km/h	rmANOVA	p	eta			
H	0.66 ± 0.17	0.83 ± 0.21	Shoe	0.127	0.121			
M	0.66 ± 0.23	0.91 ± 0.20	Speed	**<0.001**	**0.725**			
L	0.58 ± 0.18	0.83 ± 0.24	Interaction	0.505	0.042			