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The effects of different shoe stack heights and running speeds on full-body running coordination: An uncontrolled manifold analysis

Cagla Kettner [a,*], Bernd J Stetter [a,b], Thorsten Stein [a]

[a] BioMotion Center, Institute of Sports and Sports Science, Karlsruhe Institute of Technology, Karlsruhe, Germany
[b] Sports Orthopedics, Institute of Sports and Sports Science, Karlsruhe Institute of Technology, Karlsruhe, Germany

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ABSTRACT

Stack height is a highly discussed key design feature of running shoes but its effects are not well understood. This study analyzed how shoe stack height and running speed influence full-body running coordination and motor variability structure using an uncontrolled manifold (UCM) analysis. The joint angle variability (i.e. elementary variables) was analyzed in terms of its effects on a synergy stabilizing the center of mass (CoM, i.e. performance variable). A total of 17 healthy experienced runners participated and ran at 10 and 15 km/h on a treadmill with three running shoes differing in stack height (H: 50 mm, M: 35 mm, L: 27 mm). The UCM components ($UCM_{||}$, $UCM_{\perp}$ & UCM_{ratio}) were compared with statistical parametric mapping rmANOVAs for different shoes and speeds. The shoes did not show significant effects for the three UCM components. With increasing speed from 10 to 15 km/h, the joint angle coordination variability affecting the CoM ($UCM_{\perp}$) increased and UCM_{ratio} decreased independent of the shoe condition. This indicated that stack height did not influence the motor variability structure. However, independent of the shoes, the variability affecting CoM increased which led to a weakened synergy stabilizing CoM (UCM_{ratio}). It can be suggested that the variations in the tested running speeds had a greater impact on the running coordination than those of the tested shoes within the UCM framework.

1. Introduction

Running is a highly popular sports activity undertaken by millions of participants worldwide (Barrons et al., 2023). Shoe technologies are important factors affecting running performance as well as injuries (Nigg et al., 2023). In the 2010′s, advanced footwear technologies (AFT) have been emerged which are characterized by a combination of various developments; particularly carbon plates/rods infused in shoe sole that aim to optimize the shoe bending stiffness to minimize the mechanical energy loss at the ankle joints as well as a thick (≥30 mm) resilient midsole foam which provides cushioning and maximizes energy return (Rodrigo-Carranza et al., 2022). Thereby, it is essential to analyze the effects of individual shoe features to better understand their functionality (Mai et al., 2023). Stack height is a highly discussed design feature of running shoes, especially since the new regulation of World Athletics restricted the maximum height to 40 mm for road events (Ruiz-Alias et al., 2023), but the isolated effects of high stack heights on running performance are still not well understood (Burns and Tam, 2020; Hoogkamer, 2020). Previous research reported that an increased stack height may improve performance due to increased effective leg length (Burns and Tam, 2020). On the other hand, high stack heights can lead to concerns regarding decreased ankle stability (Barrons et al., 2023; Hoogkamer, 2020). To date, studies focused on a single joint degree of freedom (DoF) such as ankle joint angle in the frontal plane (Barrons et al., 2023). However, the human body is a highly redundant system with more than 200 DoF on joint level (Bernstein, 1967). Therefore, a comprehensive analysis considering all segments of the whole-body in 3D can help to understand the effects of running shoes on the coordination of running movements more comprehensively. In the context of stack height effects, such an analysis is missing.

Running coordination is essential for running performance and can be affected by many factors such as expertise level (Folland et al., 2017; Hamill et al., 2012; Möhler et al., 2020a). Although the effects of shoes on coordination have been shown by a 2D lower body UCM model and couplings of lower extremity joints (Garofolini et al., 2024; Weir et al., 2020), a 3D full-body analysis focusing on stack height effects has not yet been done. Even though most movements occur in the sagittal plane during running (van Oeveren et al., 2021), the non-sagittal planes are also important (Weir et al., 2020). Furthermore, upper body rotation increases with fatigue in long distance runs and is suggested to decrease

* Corresponding author.
E-mail addresses: cagla.kettner@kit.edu (C. Kettner), bernd.stetter@kit.edu (B.J. Stetter), thorsten.stein@kit.edu (T. Stein).

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performance (Strohrmann et al., 2012). On this basis, analyses comprising all movement planes, together with upper body movements, could improve the explanatory value of the findings. Furthermore, the effects of stack height on coordination may be pronounced at higher running speeds due to concurrent perturbations – but no study has yet addressed this issue. The rationale behind this is that a higher speed would increase signal-dependent noise (Harris and Wolpert, 1998). At a higher speed, the movements possibly become more variable due to increased noise. Consequently, the motor control system may become more sensitive to additional perturbations (e.g., shoes) and compensate them with greater difficultly.

A possible model to analyze how the motor control system coordinates the redundant human body is the uncontrolled manifold (UCM) approach (Scholz and Schöner, 1999). The UCM approach requires a model in which changes in the elementary variables (EVs, e.g., joint angles) are related to changes in a performance variable (PV, e.g., center of mass (CoM)) and analyzes how covariations of the EVs affect the PV (Scholz and Schöner, 1999). Thereby, the structure of motor variability is investigated. Within this approach the EV space is partitioned into two orthogonal subspaces (i.e. $UCM_{\|}$ and $UCM_{\perp}$). The term UCM refers to configurations of the EVs that are less controlled as long as they are located in this parallel space ($UCM_{\|}$) since these solutions do not result in a change in the PV (Latash et al., 2002). In other words, the motor control system enables EVs to exhibit high variability as long as a desired PV value can be ensured. In contrast, the solutions lying orthogonal to the UCM space ($UCM_{\perp}$) need to be controlled more strictly since in this case the covariations of EVs lead to a change in the PV. Finally, the ratio between these two UCM components (UCM_{ratio}) is used to measure the strength of a synergy that the motor control system uses to stabilize the PV. Thereby, a higher proportion of $UCM_{\perp}$ relative to $UCM_{\|}$ indicates a weaker synergy, and vice versa. Other running (Möhler et al., 2021, 2020a, 2019) and walking studies (Papi et al., 2015; Qu, 2012) used the joint angles and CoM as the EVs and PV, respectively. Previous 3D full-body running coordination analyses by UCM showed that expertise level affects running coordination, and fatigue changes the motor variability structure depending on the expertise level of the runners (Möhler et al., 2022, 2019). However, the effects of running shoes or speed have not yet been addressed in the UCM context. Garofolini et al. (2024) investigated the effects of foot strike patterns and shoe types using a 2D lower body coordination analysis with UCM, and reported a potential reliance on shoes for stability of leg length and orientation. A speed-dependent increase in stride-to-stride variability in full-body running motion was shown by a principal component analysis but the structure of motor variability has not been investigated (Maurer et al., 2013).

To our knowledge, it has not yet been analyzed how stack height and running speed affect full-body running coordination and motor variability structure. Therefore, this study aimed to analyze the effects of running shoes with different stack heights during treadmill running at different speeds with a 3D full-body UCM model. It was hypothesized that: first, higher stack heights increase the joint angle coordination variability that affects the CoM stability (i.e. no changes in $UCM_{||}$, increase in $UCM_{\perp}$ and decrease in UCM_{ratio}) (H1); secondly, higher speed increases the joint angle coordination variability that affects the CoM stability (i.e. no changes in $UCM_{||}$, increase in $UCM_{\perp}$ and decrease in UCM_{ratio}) (H2); and finally, at a higher speed the shoe effects are more pronounced due to concurrent perturbations of stack height and speed disturbing the motor control system (H3).

2. Methods

This study uses the same data set as Kettner et al. (2025). The hypotheses, modeling of running coordination and analyses in this article are original.

2.1. Participants

Sample size was oriented on related studies (Möhler et al., 2020b, 2019; TenBroek et al., 2013; Vercruyssen et al., 2016; Weir et al., 2020). The data set included 17 healthy injury-free experienced male runners (age: 25.7 ± 3.9, height: 1.78 ± 0.04 m, weight: 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 of them provided written informed consent prior to the experiment. The study was approved by the ethics committee of the Karlsruhe Institute of Technology.

2.2. Measurement protocol

The participants ran on a motorized treadmill (h/p/cosmos Saturn, Nussdorf-Traunstein, Germany). The measurement protocol lasted around 90 min in total and began with a warm-up and familiarization by running at self-selected speed with their own shoes for 5 min (Paquette et al., 2024). All participants were then given the same three test shoes in a parallelized order to carry out the measurement blocks for each shoe separately. The shoes differed mainly in their stack heights (H: 50 mm, M: 35 mm, L: 27 mm, measured at the heel; US size 9). More shoe details on shoe geometry and mass are provided in Table 1. In line with the World Athletic Shoe Regulations (World Athletics Council, 2022), the measurements were taken at the center of the forefoot and heel, which are located at 12 % and 75 % of the internal length of a shoe, respectively. H and M included AFT elements (Barrons et al., 2023) but L did not. A measurement block consisted of a familiarization to the current shoes (0 %, self-selected speed), level running (0 %, 10 km/h and 15 km/h), downhill running (−10 %, 10 km/h and 15 km/h) and uphill running (10 %, 6.5 km/h and 10 km/h). Each slope and speed condition lasted 90 s and were chosen based on test measurements and previous studies (Fadillioglu et al., 2022; Kulmala et al., 2018). There were 1 min walking breaks between slow and fast running conditions and a 2 min standing break between the slope conditions. Borg scale information (Borg, 1982) was collected before each run to control the exhaustion level (i.e. measurements did not continue unless the Borg score ≤ 12 in a 6–20 scale). This study analyzed only the level running condition (0 %).

2.3. Data acquisition, processing and biomechanical modeling

A 3D motion capture system (Vicon Motion Systems; Oxford Metrics Group, Oxford, UK; 10 Vantage V8 and 6 Vero V2.2 cameras, 200 Hz) together with 65 reflective markers were used to record the full-body kinematics. Raw kinematic data were processed with Vicon Nexus V2.12 to reconstruct and filter the markers by using a low pass Butterworth filter (4th order, cut-off frequency 10 Hz). A modified version (DoF added to the knee, ankle, elbow and hand joints; $DoF_{total} = 44$) of the Hamner Running Model (Hamner et al., 2010) in OpenSim (OpenSim V4.0) was used to calculate the joint angles necessary for UCM analysis. The model was iteratively scaled for each participant individually until the maximum marker error was less than 2 cm and the root mean square error was less than 1 cm. The weights of all markers were set as equal. Further data processing was completed in MATLAB (2023a, MathWorks Inc., Natick, USA). The initial contact events were detected based on the velocity profiles of the toe and heel markers (Leitch et al., 2011), whereas the toe-off events were identified by the maximum knee extension (Fellin et al., 2010). Both methods were robust to changes in

Table 1
Features of the running shoes.

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

foot strike mechanics and stack height. A total of 20 stance phases for the left leg were used for further calculations (Piscitelli et al., 2024). For the subsequent analyses, each stance phase was time-normalized to 101 data points.

2.4. Uncontrolled manifold approach

In line with other running (Möhler et al., 2021, 2020a, 2019) and walking studies (Papi et al., 2015; Qu, 2012) the joint angles and the CoM were chosen as EVs and PV, respectively. A 3D full-body model was used to relate the changes in EVs to those in PV for the UCM analysis.

2.5. 3D full-body model

A participant-specific anthropometric 3D full-body model (Möhler et al., 2019) consisting of 15 segments and 44 DoF (41 joint angles and 3 hip rotations) based on the Hanavan model (Hanavan, 1964) was used, in which the CoM (i.e. PV) was estimated as a function of the joint angles (i.e. EVs). The full-body CoM (rCoM) was calculated as the weighted sum of the body segments as shown in Eq. 1, where N is the total number of segments ($N = 15$); V_m the volume of the m^{th} segment; and r_m the center of gravity vector of the m^{th} segment.

$$r_{CoM} = \frac{1}{\sum_{i=1}^{N} V_m} * \sum\nolimits_{m=1}^{N} r_m V_m \tag{1}$$

2.6. Calculation of UCM components

For each time point of the stance phase, the following calculation steps were done for UCM analysis as suggested by Scholz and Schöner (1999). (1) The mean joint configuration across trials, θ^0, was calculated as an estimation of the desired configuration (Latash et al., 2007). (2) The Jacobian matrix, $J(\theta^0)$, which consists of all first-order partial derivatives of the PV with respect to each EV, was calculated at this mean joint configuration. (3) The null space of the Jacobian matrix was computed (Eq. 2). It was spanned by j-d number of basis vectors ε_i, where $j = 44$ and $d = 3$ were the number of dimensions of EVs and PV, respectively. (4) The deviation from the mean joint configuration $(\theta - \theta^0)$ was calculated and their projection on the null space was decomposed into its parallel, $\theta_{\parallel}$, and orthogonal, $\theta_{\perp}$, components (Eq. 3–4). (5) The amount of variability lying parallel to the UCM space ($UCM_{\parallel}$) and orthogonal to the UCM space ($UCM_{\perp}$) were estimated, where n was the number of stance phases (Eq. 5–6). The ratio of the two UCM components (UCM_{ratio}) was calculated using the proposed method by Papi et al. (2015) as shown in Eq. 7. A $UCM_{ratio} > 0$ indicated that there is a synergy stabilizing the CoM. Thereby, the closer the UCM_{ratio} to 1, the stronger the synergy.

$$0 = J(\theta^0)\ \varepsilon_i \tag{2}$$

$$\theta_{\parallel} = \sum_{i=1}^{j-d} \varepsilon_i^T \left(\theta - \theta^0\right) \varepsilon_i \tag{3}$$

$$\theta_{\perp} = \left(\theta - \theta^0\right) - \theta_{\parallel} \tag{4}$$

$$UCM_{\parallel} = \sqrt{\frac{1}{n\ (j-d)} \sum_{i=1}^{n} \theta_{\parallel\, i}^2} \tag{5}$$

$$UCM_{\perp} = \sqrt{\frac{1}{n\ d} \sum_{i=1}^{n} \theta_{\perp\, i}^2} \tag{6}$$

$$UCM_{ratio} = \left(\frac{2\ UCM_{\parallel}^{\,2}}{UCM_{\parallel}^{\,2} + UCM_{\perp}^{\,2}}\right) - 1 \tag{7}$$

2.7. Statistics

The time series of the three UCM components ($UCM_{\parallel}$, $UCM_{\perp}$, UCM_{ratio}) were analyzed with statistical parametric mapping (SPM) repeated measures analysis of variance (rmANOVA) by using the SPM toolbox in MATLAB (spm1d toolbox; (Pataky et al., 2019). The dependent factors were the shoe (H, M & L) and running speed (10 km/h & 15 km/h). For each UCM component ($UCM_{\parallel}$, $UCM_{\perp}$, UCM_{ratio}), a separate SPM rmANOVA was conducted. Additionally, UCM_{ratio} was tested against zero for all six conditions by using one-sample SPM t-tests. The normal distribution of data was checked by the normality tests provided in the toolbox. In case of non-normal distribution, nonparametric alternatives were conducted with 1,000 iterations. For all SPM tests, the significance level was set a priori to $\alpha = 0.05$. The partial eta squared (η_p^2) was used to estimate effects sizes of SPM ANOVA results (small effect: $\eta_p^2 \leq 0.06$; medium effect: $0.06 < \eta_p^2 < 0.14$; large effect: $\eta_p^2 \geq 0.14$).

3. Results

$UCM_{\parallel}$ showed no significant effects for the main factors shoe (Fig. 1, left column), speed (Fig. 2, left column) or their interactions (Fig. 3, left column).

$UCM_{\perp}$ revealed no significant effects for the main factor shoe (Fig. 1, middle column). It was lower at 10 km/h compared with 15 km/h with an F statistic exceeding the threshold over the whole stance phase (Fig. 2, middle column) with high effect sizes (Supplementary Fig. 1). The interaction between shoe and speed conditions was not significant (Fig. 3, middle column).

UCM_{ratio} did not show any significant shoe effects (Fig. 1, right column). UCM_{ratio} showed a speed effect from 30 to 100% of the stance phase. It was higher at 10 km/h than at 15 km/h, indicating a weaker synergy at a higher speed, with the F statistic exceeding the threshold for most of stance phase (30–100 %, Fig. 2, right column) with high effect sizes (Supplementary Fig. 1). The interaction between shoe and speed conditions was not significant (Fig. 3, right column). Furthermore, UCM_{ratio} was larger than 0 for all shoe and speed conditions indicating that the CoM was stabilized by a synergy (Fig. 4).

4. Discussion

This study investigated the effects of running shoes with three different stack heights during treadmill running at 10 km/h and 15 km/h on full-body running coordination using UCM approach. In contrast to H1, no shoe effects on running coordination or motor variability structure were detected. In line with H2, at the higher speed the variability affecting CoM increased independent of the shoes. However, a higher speed did not result in more pronounced shoe effects, which contradicts H3.

4.1. Differences in tested stack heights did not affect running coordination

The shoes did not affect running coordination or motor variability structure, in contrast to both H1 and previous studies (Garofolini et al., 2024; Weir et al., 2020). More concretely, Weir et al. (2020) showed that the coefficient of variation of the lower limb couplings (e.g., thigh and leg coupling in the sagittal plane) increased in neutral shoes compared with the stability shoes (i.e. a medial post added to neutral shoes). However, they did not investigate any stack height effects and analyzed the variability with a 2D lower body analysis without decomposing it in terms of its effects on a PV. Therefore, comparison with the current study is difficult. Garofolini et al. (2024) reported that the most minimalist shoes (Vibram® Five fingers, minimalist index (MI) = 96 %) increased stabilization of leg length but not leg orientation across strides compared to the shoes with lower MI (Mizuno® Wave Rider 21, MI = 18 %; Mizuno® Wave Sonic, MI = 56 %). However, they did not particularly

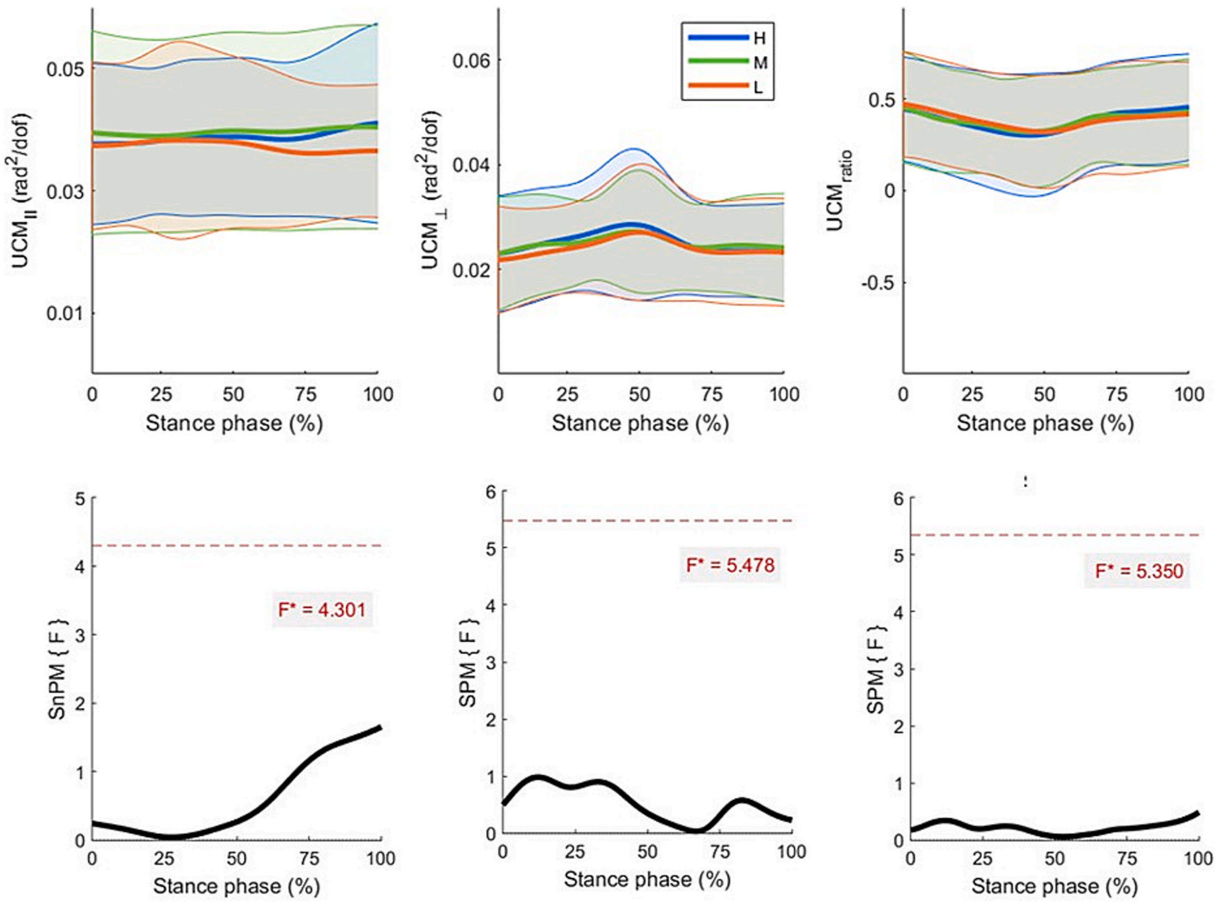

Fig. 1. Upper row shows the results for the three UCM components ($UCM_{\|}$, $UCM_{\perp}$ and UCM_{ratio}) for different shoes (H: 50 mm, M: 35 mm and L: 27 mm) as mean (thicker lines) ± standard deviations (upper and lower thinner lines). The average of two running speed conditions are represented for each shoe condition. Lower row shows the corresponding SPM rmANOVA results for the main factor shoe. F* values indicate the corresponding thresholds for $\alpha = 0.05$.

analyzed stack height effects, used a 2D lower body model with leg length and orientation as PV, which makes it difficult to compare their results with the current study. In short, other studies reported shoe effects but they did not focus on stack height effects or full-body coordination.

A previous study with the same data set (Kettner et al., 2025) showed that the tested shoes affected both running style and stability. More precisely, H compared to M led to longer steps with longer stance time and increased vertical oscillation of the CoM. Furthermore, the local dynamic stability of the hip was lower with H than L in the vertical direction based on a nonlinear analysis. It should be noted that these differences between H and L may also be attributed to the carbon rods infused in H and not solely to the higher stack heights. Nevertheless, the results of the previous study, combined with this study, indicated that the stride-to-stride variability remained stable although the mean values of the discrete parameters of running style and local dynamic stability of the hip changed. These findings do not contradict each other but stem from different methodological approaches. Variability analysis in this study provides insights into how the motor control system coordinates redundant DoF across multiple strides to stabilize an important PV (i.e., CoM), whereas running style parameters describe the running style without considering the changes between the strides (i.e., stride-to-stride variability). Furthermore, hip stability using the maximum Lyapunov exponent reveals additional insights into inherently nonlinear human movements without any linearity assumptions (McCamley and Harrison, 2016). One explanation for the lack of shoe effects on the structure of motor variability may be that the tested shoe configurations provide only small perturbations to the motor control system (Prejean and Ricard, 2019). Therefore, they were possibly compensated by small adjustments which were not captured by UCM analysis. Another explanation may be that the responses of participants to the tested shoes were individual, which complicated the detection of changes across all participants (Koegel et al., 2024; Mai et al., 2023).

4.2. Joint angle coordination variability affecting CoM movement increases with increasing speed

The results revealed that the joint angle coordination variability that does not influence the CoM stability ($UCM_{\|}$) did not change between the running speeds. However, the joint angle coordination variability affecting the CoM stability ($UCM_{\perp}$) was higher at 15 km/h. Consequently, the synergy stabilizing the CoM (UCM_{ratio}) became weaker at 15 km/h. These findings were in line with the second hypothesis (H2). The increased $UCM_{\perp}$ with increasing speed in this study may be explained by the increased noise in the system due to larger control signals associated with faster movements (Harris and Wolpert, 1998). More concretely, moving faster may require larger control signals that affect the PV, which was the CoM in this study. Increased noise due to larger control signals was observable in $UCM_{\perp}$, and not in $UCM_{\|}$, possibly because the noise was compensated by the covariations of EVs in the $UCM_{\|}$ space. Nevertheless, analyzing such a change by decomposing the PV variability was beyond the scope of this study. Further studies may apply a tolerance, noise and covariation analysis to investigate the structure of CoM variability changes between two running speeds (Möhler et al., 2021; Müller and Sternad, 2004).

Previous studies analyzing the effects of speed on running coordination by lower extremity couplings in 2D reported conflicting results. For example, Bailey et al. (2018) showed that the coupling patterns

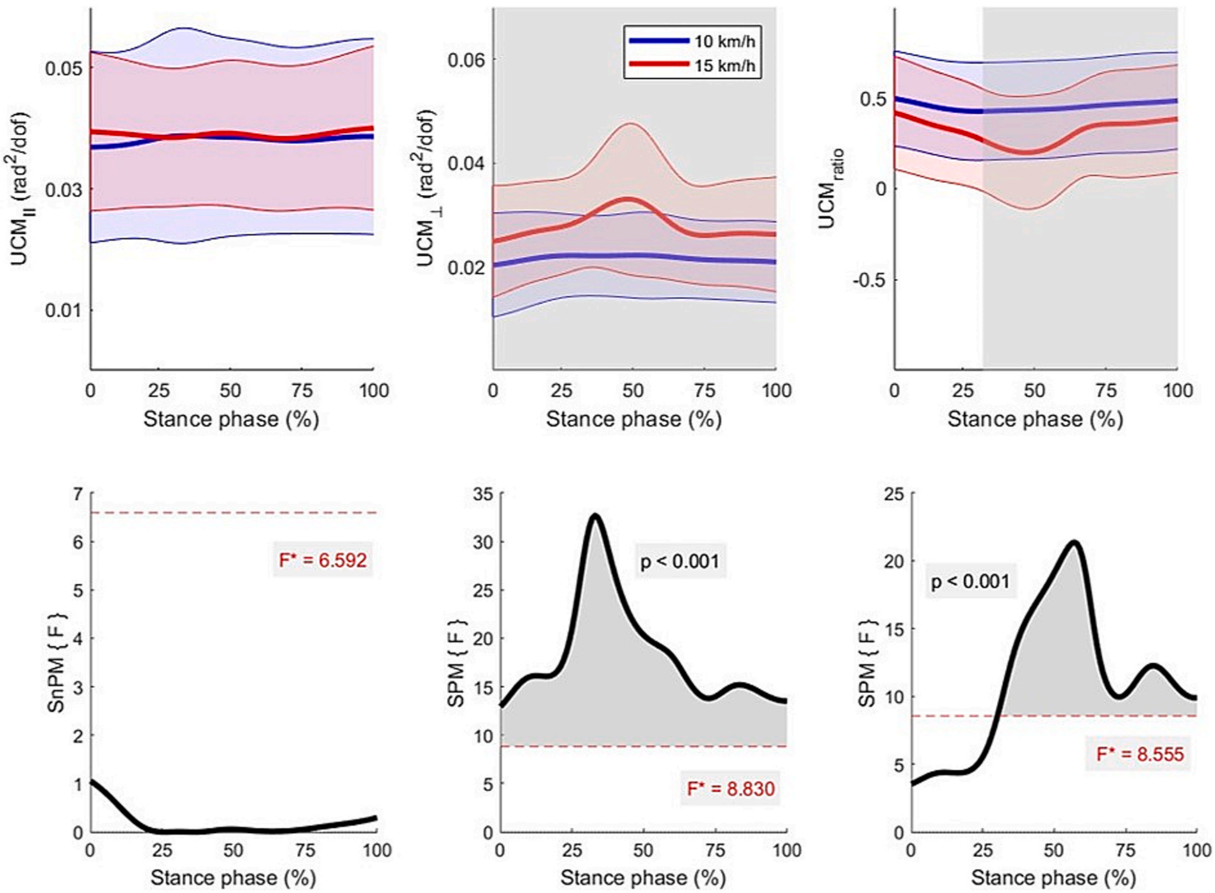

Fig. 2. Upper row shows the results for the three UCM components ($UCM_{\parallel}$, $UCM_{\perp}$ and UCM_{ratio}) for different running speeds (10 km/h and 15 km/h) as mean (thicker lines) ± standard deviations (upper and lower thinner lines). The average of three shoe conditions are represented for each running speed. The significant speed effects in SPM rmANOVA are shown as the gray areas. Lower row shows the corresponding SPM rmANOVA results for the main factor speed with clustered p-values. F* values indicate the corresponding thresholds for α = 0.05.

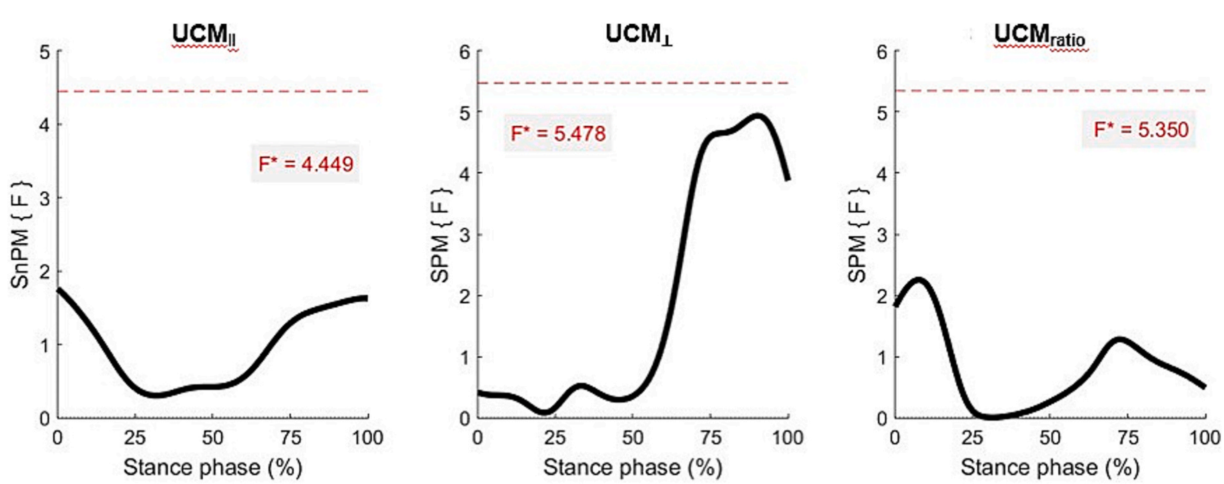

Fig. 3. SPM rmANOVA results for the interaction effects between shoe and speed conditions. F* values indicate the corresponding thresholds for α = 0.05.

change between different running speeds, whereas Abbasi et al. (2020) and Floría et al. (2019) did not find any differences. Abbasi et al. (2020) attributed these conflicting results to the varying speeds across the studies. Bailey et al. (2018) reported that increasing the running speed from −25 % of the preferred speed to + 100 % resulted in more constrained running pattern but they did not report the tested speeds in m/s. In contrast, the current study showed an increase in joint angle coordination variability, particularly in the variability component that leads to changes in PV (i.e. $UCM_{\perp}$). Possible reasons for the varying results between the current study and Bailey et al. (2018) are the varying running speeds and methodical approaches. This study used UCM analysis with a 3D full-body model considering the coordination of 44 DoF, whereas Bailey et al. (2018) conducted a joint coupling analysis of the lower body extremities in 2D which enabled binary consideration of joints at once (e.g., thigh and leg coupling in the sagittal plane).

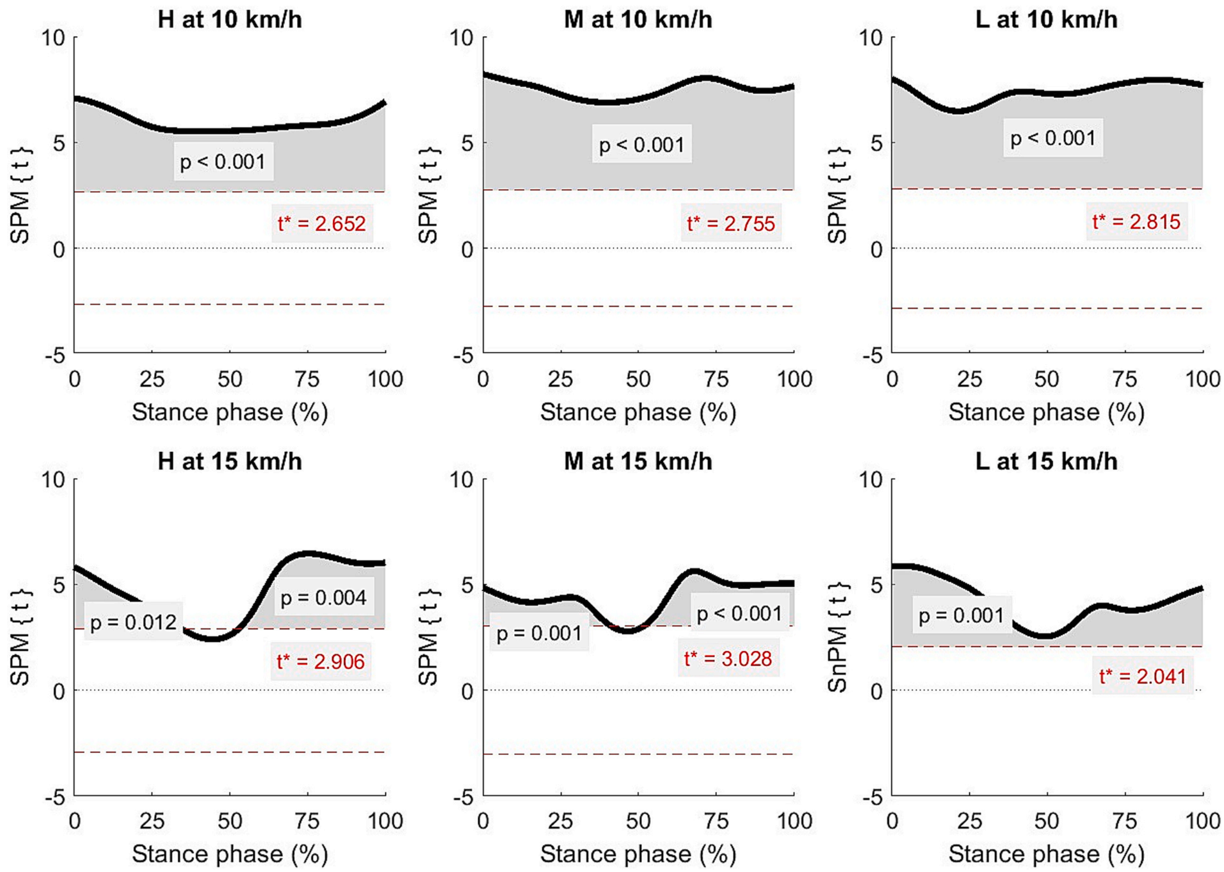

Fig. 4. One sample SPM *t*-test results of UCM_{ratio} for different shoe (H: 50 mm, M: 35 mm and L: 27 mm) and speed conditions (10 km/h and 15 km/h). The significant speed effects in SPM t-tests are shown as the gray areas with clustered p-values. t* values indicate the corresponding thresholds for $\alpha = 0.05$.

4.3. No shoe effects on running coordination even at a higher speed

The third hypothesis in this study (H3) stated that the shoe effects would be pronounced at a higher speed due to the concurrent perturbations. The rationale behind this hypothesis was that a higher speed would increase signal-dependent noise (Harris and Wolpert, 1998), which may make the motor control system more sensitive to additional perturbations (e.g., shoes) and compensate them with greater difficulty. The results revealed no interaction effects of running speed and shoes. Based on these findings, H3 must be rejected. Similar to main shoe effects, one explanation may be that the perturbations due to the tested shoes were too small (Prejean and Ricard, 2019); therefore, even at a higher speed there were no shoe effects. The results showed that the variations in running speeds had a greater effect on running coordination than the shoes using a UCM analysis.

4.4. Limitations

This study has some limitations that should be considered. First, the shoes differed mainly in their stack heights but other features were not the same. The mass of the shoes inevitably differed slightly (max difference 49 g; Table 1). An added mass of 50 g leads to no changes in running economy or spatio-temporal characteristics (Rodrigo-Carranza et al., 2020) but it is not known if it may affect the movement variability and its structure. Furthermore, H and M were produced using AFT (Barrons et al., 2023) but L used conventional approaches with non-equivalent stack differences between shoes. Secondly, UCM results were suggested to depend on the chosen EVs and PV (Möhler et al., 2021). Even though the CoM was used as PV in various running (Möhler et al., 2021, 2020a, 2019) and walking studies (Papi et al., 2015; Qu, 2012), other PVs are also possible (Krishnan et al., 2013). Nevertheless, the CoM movement was suggested to be essential for the running task (van Oeveren et al., 2021). This study analyzed the CoM in 3D aiming at consideration of full-body movements in all possible directions. Future studies may consider movements in individual planes to focus on specific movements of CoM (e.g., vertical). It is important to note that the movements in non-sagittal planes are harder to simulate, and the outputs may vary between used kinematics models. However, it is generally hard to validate the model outputs but only a comparison between models is possible. Thirdly, the used UCM analysis was possibly not sensitive enough to reveal effects of different shoes. Further studies may consider redundancy at the level of muscle activations (Latash, 2024). Fourthly, the sample size was oriented on previous comparable studies but a power analysis was not conducted. Even though, the sample was in the current study was larger than that of comparable studies and the effects sizes were large, future studies may benefit from larger sample sizes to increase the power. Lastly, the participants ran on a treadmill as in various gait and running studies with a UCM approach (Garofolini et al., 2024; Qu, 2012). Even though a treadmill run allows to record a large number of cycles with high accuracy and under the same conditions for all participants (e.g., speed), it may modulate the variability structure (Lindsay et al., 2014). Furthermore, only two running speeds were compared and the participants were experienced male runners in a non-fatigued state. The detected effects in this study may not necessarily be transferable to other groups or conditions.

5. Conclusion

This study investigated the effects of shoe stack heights and running speeds on full-body coordination and motor variability structure with a UCM analysis. The key findings were that the tested shoes did not affect either. However, independent of the stack height, increasing speed meant that the joint angle coordination variability affecting the CoM increased and the synergy stabilizing CoM became weaker. These results indicated that the variations in the tested running speeds had a greater impact on full-body running coordination than variations in the tested running shoes.

6. Data statement

The datasets recorded during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Source of funding

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.

CRediT authorship contribution statement

Cagla Kettner: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bernd J Stetter:** Writing – review & editing, Conceptualization. **Thorsten Stein:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing 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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2025.112615.

Data availability

Data will be made available on request.

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