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Neuromechanical stabilisation of the centre of mass during running

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ABSTRACT

Background: Stabilisation of the centre of mass (COM) trajectory is thought to be important during running. There is emerging evidence of the importance of leg length and angle regulation during running, which could contribute to stability in the COM trajectory The present study aimed to understand if leg length and angle stabilises the vertical and anterior-posterior (AP) COM displacements, and if the stability alters with running speeds.

Methods: Data for this study came from an open-source treadmill running dataset (n = 28). Leg length (m) was calculated by taking the resultant distance of the two-dimensional sagittal plane leg vector (from pelvis segment to centre of pressure). Leg angle was defined by the angle subtended between the leg vector and the horizontal surface. Leg length and angle were scaled to a standard deviation of one. Uncontrolled manifold analysis (UCM) was used to provide an index of motor abundance (IMA) in the stabilisation of the vertical and AP COM displacement.

Results: IMA_{AP} and $IMA_{vertical}$ were largely destabilising and always stabilising, respectively. As speed increased, the peak destabilising effect on IMA_{AP} increased from −0.66(0.18) at 2.5 m/s to −1.12(0.18) at 4.5 m/s, and the peak stabilising effect on $IMA_{vertical}$ increased from 0.69 (0.19) at 2.5 m/s to 1.18 (0.18) at 4.5 m/s.

Conclusion: Two simple parameters from a simple spring-mass model, leg length and angle, can explain the control behind running. The variability in leg length and angle helped stabilise the vertical COM, whilst maintaining constant running speed may rely more on inter-limb variation to adjust the horizontal COM accelerations.

1. Introduction

Recreational running is a very popular activity undertaken by people of many ages [1], undertaken almost anywhere, both indoors and outdoors. When running outdoors, humans encounter and manage undulating surfaces (e.g. curbs, potholes) with ease, tuning their leg mechanical properties to ensure consistent centre of mass (COM) trajectory [2–4]. Human motor control has at its disposal many strategies to achieve a given task goal, such as stabilising (i.e. reducing variability) the COM trajectory. Stabilisation of the vertical COM trajectory is thought to be important to optimise the energetic cost of running [5]. In the anterior-posterior (AP) direction, stability of the COM trajectory relative to the stance limb [6] is required to maintain constant-speed running.

To stabilise the COM trajectories in running, a previous study proposed that the variability of lower-limb segment angles was harnessed [7]. To understand how patterns of variability between individual functional units (e.g. between leg length and angle) are harnessed to stabilise a motor goal, the Uncontrolled Manifold (UCM) analysis has been used [8]. In UCM, the variability between two or more functional units is decomposed into two variance measures: one where the variance in functional units does not increase the variability of the goal (Goal-Equivalent Variance [GEV]), and another where variance increases the variability of the goal (Non Goal Equivalent Variance [NGEV]). Previous studies have also proposed that the motor control system adopts a hierarchical model of organising the patterns of variability. For example, in a UCM study performed on lower-limb kinetics in walking, variability in joint moments was used to stabilise individual limb forces, but not completely. Residual variation in limb-level forces were then used to stabilise the total force applied by the two limbs [9,10].

In vertical hopping leg length and angle are themselves task goals that are stabilised by the variability of segment angles [11,12]. Given

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the dynamic similarity between running and hopping, we anticipate that both leg length and angle would represent task goals that are stabilised. Based on the hierarchical model of control proposed previously [9,10], we propose that leg length and angle are themselves acting as functional units to stabilise the higher levels of task goal in running – COM trajectory. There is evidence that leg length and angle variability could be used for stabilising the COM trajectory, from physics-based human locomotion models, human and animal perturbation studies [13–16] (Fig. 1). Stability in the step-to-step variation in vertical COM trajectory can be achieved by compensatory changes to both leg length and angle [14]. A more acute leg angle will require an increase in leg length, and vice-versa, to stabilise the vertical COM trajectory. A previous study reported that faster running velocities require either a greater leg stiffness brought about by a reduction in leg length change, without a change in leg angle, or a more acute leg angle, without a change in leg stiffness [14].

This study aims to investigate if the step-to-step variability in leg length and angle are exploited to stabilise the COM trajectory during human running. The secondary aim is to investigate if the motor control strategy of covarying leg length and angle differ at different running speeds. Our primary hypothesis is that leg length and angle would covary to stabilise both the vertical and anterior-posterior (AP) COM trajectories. Given that a previous study in walking reported that the variance components of GEV and NGEV remain unaltered across speeds [17], we hypothesise that the strength of stability of the vertical and AP COM trajectories will not vary with increasing running speed.

2. Methods

2.1. Data

Data for the current study came from a publicly available dataset on running (n = 28; 27 male, 1 female) in healthy adults (mean [standard deviation] of age 34.8 [6.7] years, mass 69.6 [7.7] kg, height 176.0 [6.8] cm; self-reported weekly running volume of 16–25 km [n = 1], 26–35 km [n = 9], 36–45 km [n = 7], 45 km [n = 2], > 45 km [n = 9]; running pace of 4.1 [0.4] min/km) [18]. Running assessment was performed using a dual-belt, force-instrumented treadmill (300 Hz; Bertec, USA), and the motion was captured with 12 optoelectronic cameras (150 Hz; Motion Analysis Corporation, USA) [18]. Participants performed shod running across three fixed speeds of 2.5 m/s, 3.5 m/s, and 4.5 m/s [18]. Marker trajectories and GRF were collected for 30 s and the data were low-pass filtered at a matched frequency of 12 Hz (4th Order, zero-lag, Butterworth) [19]. Biomechanical modeling was performed in Visual 3D software (C-motion Inc., Germantown, MD, USA). A force plate threshold of 50 N was used to determine gait events of initial contact and toe-off. A seven-segment lower limb inertial model was created [18].

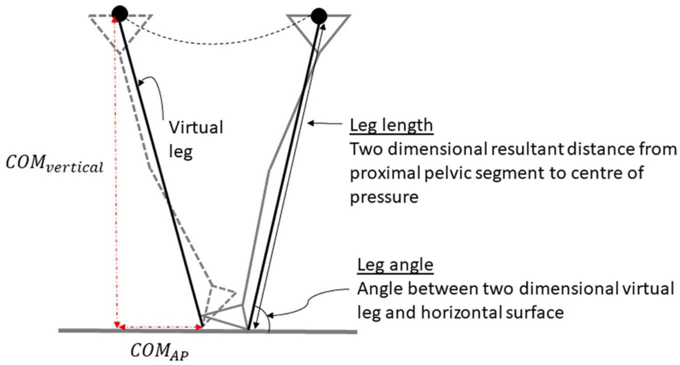

Fig. 1. Schematic illustration of the two-dimension kinematic leg model used. Abbreviations: COM – centre of mass; AP – anterior posterior.

2.2. Biomechanical processing

A virtual "pelvis" landmark was calculated using the proximal endpoint of the modelled inertial pelvic segment [20,21] (Fig. 1). A two-dimensional (2D), sagittal plane, virtual leg was created between the proximal end of the pelvis and the centre of pressure (COP) (Fig. 1). Leg length (m) was calculated by taking the resultant distance of the 2D sagittal plane leg vector (Fig. 1). Leg angle (rad) was defined by the angle subtended between the leg vector and the horizontal surface (Fig. 1). Both leg length and angle were time normalized to 101 data points within the stance phase of each lower limb. The total (combined left and right) number of trials used for UCM analysis varied per participant and speed. The minimum number of total trials was 29 and the maximum was 56 (interquartile range [IQR] 25th and 75th percentile 40 and 45).

2.3. UCM analysis

Eqs. 1 and 2 represent the geometric relationships mapping the variables of leg length and angle to the outcomes of COM vertical and anterior-posterior, respectively:

$$COM_V = Length \times \sin(angle) \tag{1}$$

$$COM_{AP} = Length \times \cos(angle) \tag{2}$$

2.3.1. Uncontrolled manifold – step 2 (Jacobian)

For every UCM analysis, leg length and angle were first scaled to a standard deviation of one [22]. The UCM analysis was carried out using a previously published method [23], for each of the 101 stance data points:

$$C = \begin{bmatrix} \sigma^2_{length} & \sigma_{length,angle} \\ \sigma_{angle,length} & \sigma^2_{angle} \end{bmatrix} \tag{3}$$

$$GEV = \frac{trace\left(null(\boldsymbol{J})^T \cdot \boldsymbol{C} \cdot null(\boldsymbol{J})\right)}{n-d} \tag{4}$$

$$NGEV = \frac{trace\left(orth(\boldsymbol{J}^T)^T \cdot \boldsymbol{C} \cdot orth(\boldsymbol{J}^T)\right)}{d} \tag{5}$$

$$TotV = \frac{trace(C)}{n} \tag{6}$$

$$IMA = \frac{GEV - NGEV}{TotV} \tag{7}$$

where C is the covariance matrix, where $\sigma_i^2$is the individual variance of a single kinematic variable (leg length or angle), and $\sigma_{ij}^2$is the covariance between two kinematic variables (length and angle) (Eq. 3); J is the Jacobian matrix mapping infinitesimally small changes in predictor variables (leg length, angle) to changes in COM displacement; *null* and *orth* create orthonormal bases for the null and column space of the (transposed) Jacobian matrix, respectively; GEV represents the variability of both leg length and angle that stabilises the COM displacement (Eqn 4); NGEV represents the variability of both leg length and angle that perturbs the COM displacement (Eq. 5); TotV is the total kinematic variance (Eqn 6); index of motor abundance (IMA) (Eq. 7) where an IMA > 0 represents more variability in leg length and angle used to stabilise the COM displacement, and an IMA < 0 more variability in leg length and angle used to perturb the COM displacement [12]; d is the degree of freedom in the performance variable (d = 1 in this study); and n is the degree of freedom in the elemental variables (n = 2).

2.4. Statistical inference

All statistical analyses were performed using R (version 4.1.2) and the R package *mgcv* [24]. The main outcomes in this study were the IMA values. We model the IMA of subject i, leg side j, at the k^{th} % cycle point in stance, for speed l as a Generalised Additive Model (GAM) [24], given by the following equation:

$$IMA_{ijklm} = \alpha + \beta_{subject,i} + \beta_{side,j} + \beta_{speed,l} + \beta_{trial,m} + f_{jl}(cycle_k) + \varepsilon_{ijklm}$$

The IMA is modelled by a global intercept α, a random intercept $\beta_{subject,i}$ for every subject, a leg side effect $\beta_{side,j}$ for the side of the leg, a speed effect $\beta_{speed,l}$ for the three different speeds, a trial effect $\beta_{trial,m}$ for the number of trials m used for UCM analysis, and a smooth cycle effect $f_{jl}(cycle_k)$ (represented by 10 thin plate regression spline basis functions [24]). Due to the varying number of trials used for UCM analysis, the inclusion of trial as a covariate was to partial its effect out during subsequent pairwise difference calculations.

We first quantified the predicted mean IMA for each running speed with the 95% confidence intervals (CI), to determine if the IMA was significantly stabilising or destabilising. Next, to infer the differences in smooth effects between different speed values, we calculated the pairwise marginal difference, with their 95% CI, between two smooth effects of different speed values for a given leg side. Significance was defined when the 95% CI of our predicted mean values did not contain zero [25].

3. Results

The mean and standard deviation waveform plots of all kinematic variables used for UCM analysis showed no differences across left and right side (Fig. 2). Overall, IMA_{AP} and $IMA_{Vertical}$ demonstrated reciprocal patterns (Fig. 3).

IMA_{AP} was largely destabilising with 58–71 data points across the running stance having a 95%CI width that was below zero (Fig. 4a). There is a period around mid-stance where IMA_{AP} was stabilising with three to 12 data points across stance having a 95%CI above zero. At initial contact, IMA_{AP} was between −0.38 (95%CI −0.42 to −0.35) at 2.5 m/s to −0.74 (95%CI −0.79 to −0.69) at 4.5 m/s (Fig. 4a). At toe-off, IMA_{AP} was between −0.60 (95%CI −0.63 to −0.56) at 2.5 m/s to −1.03 (95%CI −1.08 to −0.98) at 4.5 m/s (Fig. 4a). IMA_{AP} peaked in its stabilising effect at 48% stance (0.02, 95%CI 0.001–0.04) at 2.5 m/s, 46% stance (0.03, 95%CI 0.001–0.06) at 3.5 m/s, and 43% stance (0.05, 95% 0.02–0.08) at 4.5 m/s (Fig. 4a).$IMA_{Vertical}$ was always stabilising with the greatest effect observed during initial contact and toe-off. At initial contact, $IMA_{Vertical}$ was between 0.47 (95%CI 0.44–0.51) at 2.5 m/s to 0.84 (95%CI 0.79–0.89) at 4.5 m/s (Fig. 4b). At toe-off, $IMA_{Vertical}$ was between 0.72 (95%CI 0.68–0.75) at 2.5 m/s to 1.17 (95%CI 1.13–1.22) at 4.5 m/s (Fig. 4b).

In the AP axis, when comparing 3.5–2.5 m/s, IMA was significantly lower between 0% and 29%, and between 85% and 100% as running speed increased (Fig. 4c). When comparing 4.5–2.5 m/s, IMA was significantly lower between 0% and 7% and 71–100% of stance, but significantly greater between 9% and 24% stance as speed increased (Fig. 4c). When comparing 4.5m/s to 3.5 m/s, IMA was significantly lower between 0% and 4% and 68–100% stance, but significantly greater between 6% and 36% stance as speed increased (Fig. 4c).

In the vertical axis, when comparing 3.5–2.5 m/s, IMA was significantly greater between 0% and 30%, 43–47%, and 86–100% as running speed increased (Fig. 4d). When comparing 4.5m/s to 2.5 m/s, IMA was significantly greater between 0% and 7%, 42–49%, and 71–100% of stance, but significantly lower between 10% and 21% stance as speed increased (Fig. 4d). When comparing 4.5m/s to 3.5 m/s, IMA was significantly greater between 0% and 4% and 68–100% of stance, but significantly lower between 7% and 29% stance as speed increased (Fig. 4d).

4. Discussion

There is emerging evidence that leg length and leg angle are two candidate functional units [13–15] that may be regulated to ensure consistent COM trajectory [26]. In partial support of the primary hypothesis, variability in leg length and angle was exploited to always stabilise the vertical COM trajectory and largely to destabilise the AP COM trajectory. The stabilising and destabilising effects of variability for the vertical and AP COM peaked at both initial contact and toe-off of

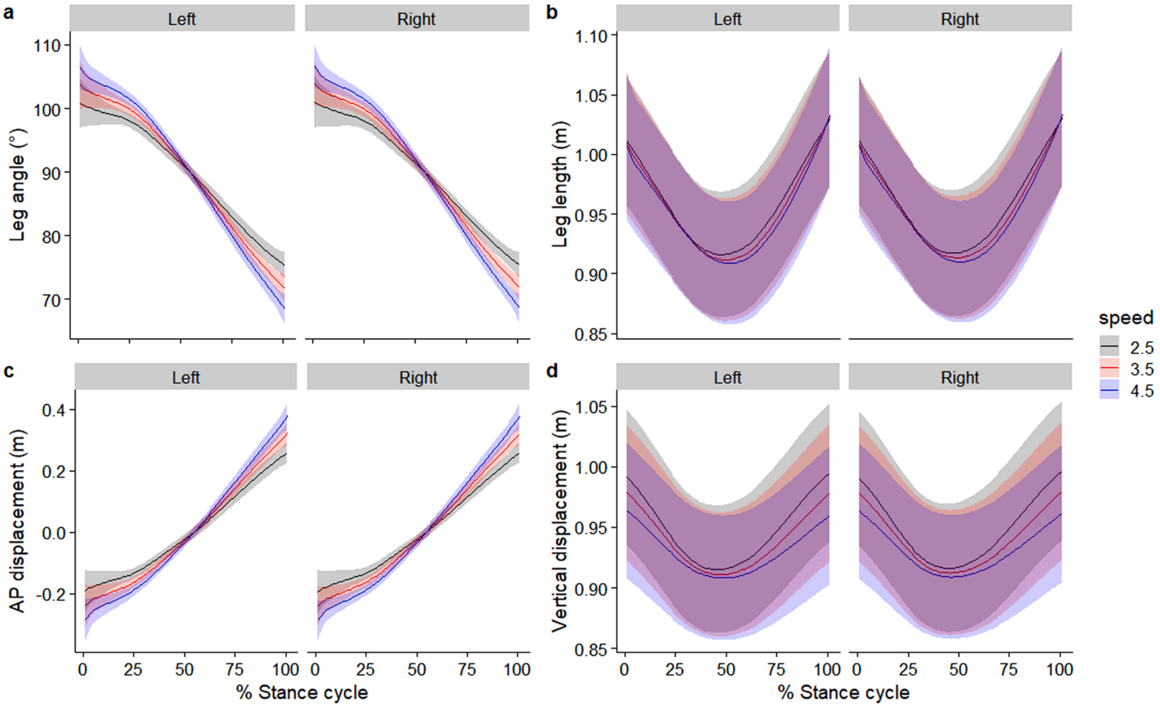

Fig. 2. Mean with error cloud as one standard deviation of lower leg kinematics during the stance phase of running.

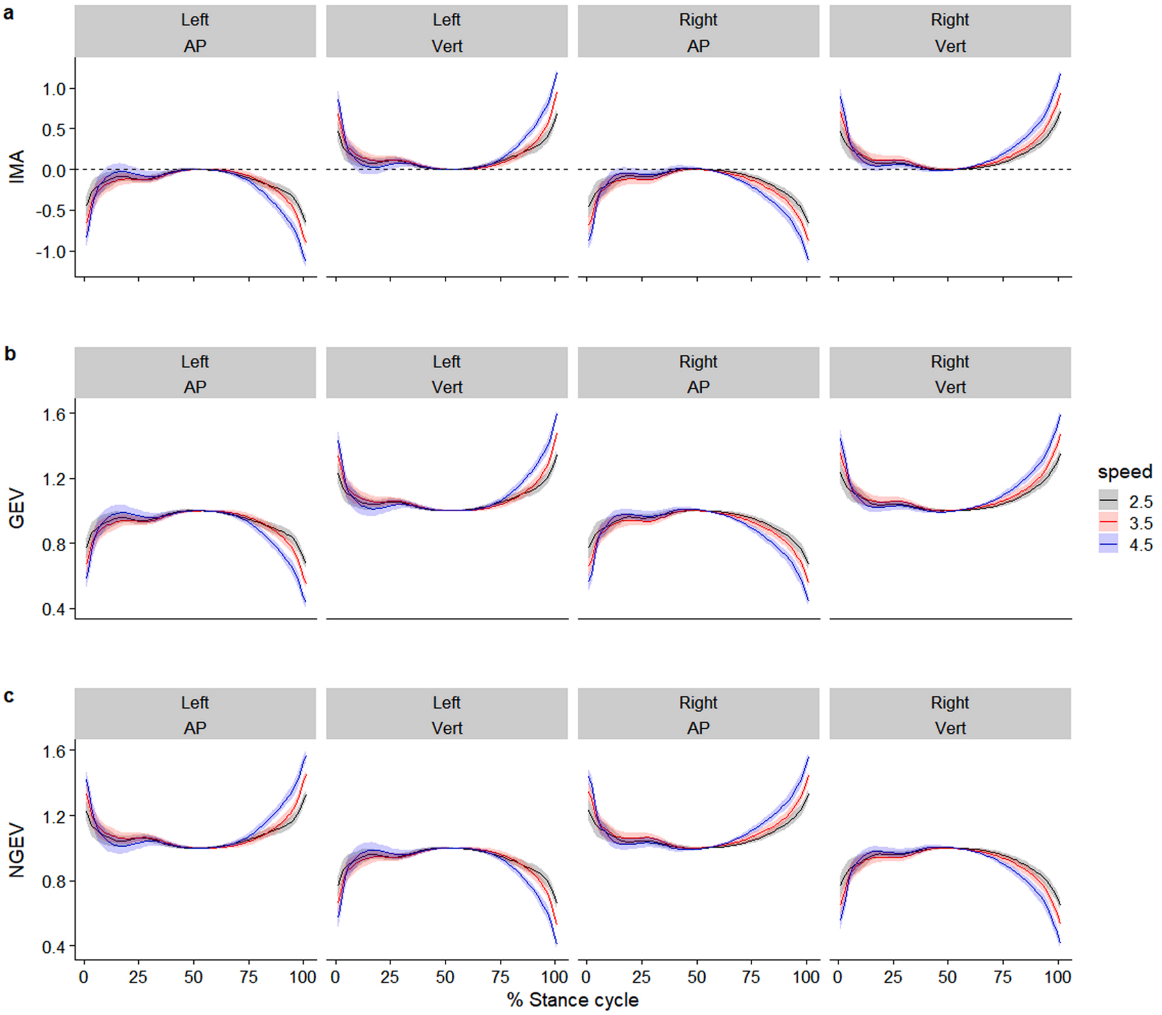

Fig. 3. Mean with error cloud as one standard deviation of lower leg variances and their ratio during the stance phase of running. Abbreviations: IMA – index of motor abundance; GEV – goal-equivalent variance; NGEV – non-goal equivalent variance.

running. Contrary to the second hypothesis, as speed increases, the stabilising effect of variability in the vertical axis at initial contact and toe-off became stronger, whilst the destabilising effect in the AP axis in the same phases also became stronger.

The present finding that the variability between leg length and angle was used to always stabilise the vertical COM trajectory, is consistent with the literature on the link between excessive vertical COM oscillations and impaired energetic cost during running [5,27]. In a 5 km running time trial, runners adjusted their running speed but kept invariant the vertical oscillation of their COM, suggesting that regulation of the vertical COM displacement represents a high priority for the motor control system [28]. A previous work that performed a UCM analysis on a 2D kinematic model using segment angles reported that the COM trajectory is stabilised by the variability during running, but it did not differentiate the control along different axes [7].

Interestingly, one study using UCM, reported that stabilisation of the COM trajectory increased from a minimum at initial contact to a maximum at toe-off [7], although the study did not distinguish the control along the vertical or AP direction. This is opposite to the findings of the present study where the strength of stabilisation of the vertical COM was greatest at both initial contact and toe-off, but least during mid-stance. However, a previous study reported that stabilisation of the vertical GRF using individual joint moments peaked at initial contact, mid-stance, and toe-off in vertical hopping [29]. It is thought that stabilisation of the vertical COM displacement at mid-stance is particularly important, given that this is energetically the most expensive phase of motion [12]. The peak stabilisation of the vertical COM during initial contact supports previous works that demonstrated that leg posture at initial contact determines limb function during the stance phase [30–32], whilst at toe-off, it determines the aerial time, which in turn influences the minimum time available for limb repositioning [12].

A previous UCM study in vertical hopping reported that the stabilisation of leg length as the outcome was lowest during stance at initial contact and toe-off (inverted “U” shaped pattern), whilst the stabilisation of leg angle as the outcome, peaked at the same phases (“U” shaped pattern) [12]. If both the patterns of leg length and angle stabilisation were in phase, there may be insufficient residual variability in these two variables to support stabilisation of the COM displacement. Hence, the out-of-phase stabilisation of leg length and angle could be a mechanism that supports harnessing the variability of these two variables to stabilise the vertical COM displacement. Interestingly, the present study’s 2DOF system (leg length and angle) was able to stabilise two COM outcome goals [12], albeit only during a small period around mid-stance. The period of maximal stabilisation of the AP COM occurred when the stabilisation of the vertical COM displacement was lowest. The present findings suggest that even though the motor control system can stabilise all outcomes and operate within a non-redundant system [33], it does not do so for most of the running stance phase.

The stabilisation of the vertical, and not the AP COM for most of the running stance, occurred despite participants having to run at a steady-

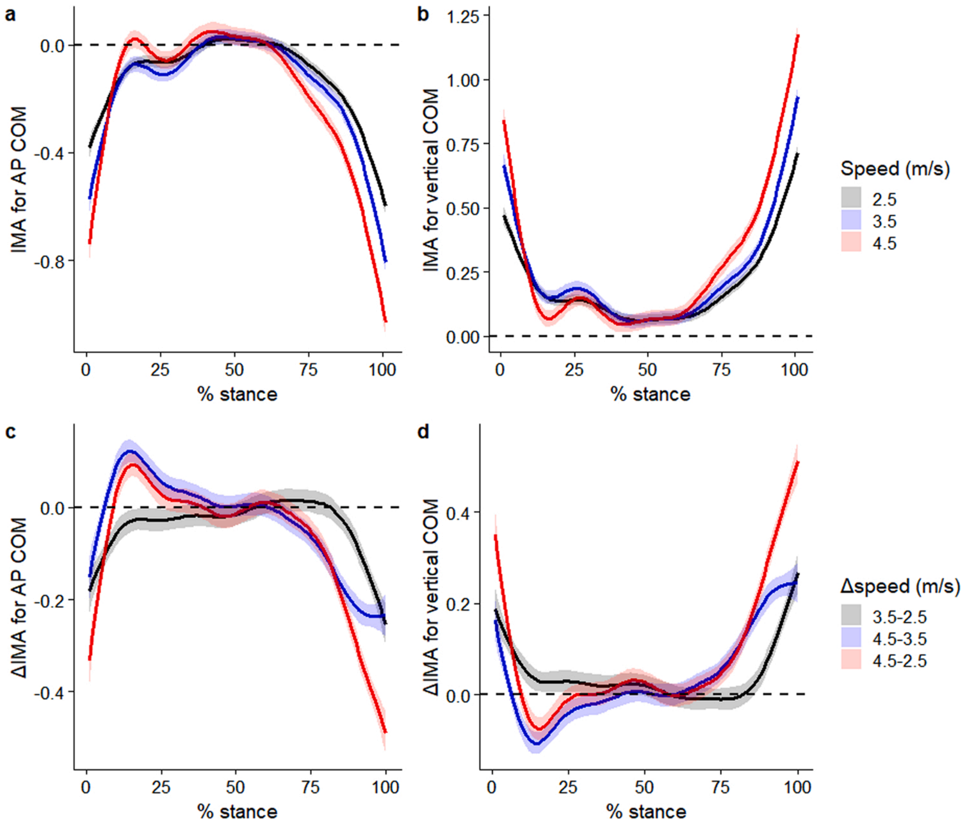

Fig. 4. Mean with error cloud as 95% confidence interval of the predicted: a) mean IMA for the stabilisation of the anterior-posterior COM, b) mean IMA for the stabilization of the vertical COM, c) mean difference between speeds in the IMA for the stabilization of the anterior-posterior COM, and d) mean difference between speeds in the IMA for the stabilisation of the vertical COM. Abbreviations: IMA – index of motor abundance.

state velocity on a treadmill. The AP position between the foot and COM determines the forward velocity of locomotion [34] by influencing the braking and propulsive AP forces. In addition, the AP COP-COM position also determines the AP position of the participant on the treadmill, and one would expect that AP COM stabilisation would be prioritised to prevent a fall off the treadmill. The present findings were consistent with a prior study in walking which reported that the AP GRFs of the two limbs in the double support phase destabilised the net AP GRF [9]. The motor control system could use this variation between both right and left limbs to adjust the horizontal COM accelerations to maintain constant running speed and position on the treadmill. The motor control system appears to prioritise motor redundancy and exploits multiple strategies toward fulfilling multiple task goals [33].

The strengthening of the stabilising and destabilising effects on the vertical and AP COM, respectively, with increasing speed in the present study, was not supported by a study in walking [17]. The previous study investigated the stabilising effects of lower-limb sagittal plane kinematics on the COM during walking [17]. To our knowledge, only one other study in running used UCM to investigate the control of the COM at speeds of 10 km/h (2.8 m/s) and 15 km/h (4.2 m/s) [35]. Although no statistical comparison was performed between speeds in the previous study, visual inspection suggests no changes in stabilisation of COM control at different running speeds [35]. However, in a dynamically similar task of vertical hopping, leg length and angle stabilisation during initial contact and toe-off increased when hopping frequency increased [12]. If the motor control of leg length and angle during hopping and running were exactly similar, we would expect that as running speed increases, the stabilisation of the vertical COM would decline during initial contact and toe-off. This suggests potential different strategies in the way leg length and angle are used to stabilise the COM that are task dependent.

The control of leg length and angle in the stabilisation of COM displacements may differ between overground compared to treadmill running, given that the vertical COM displacement in the former is greater than the latter [36]. Also, given that this dataset comprised predominantly of male participants, and that prior studies have reported differences in the regulation of leg stiffness [37], extrapolating our findings to female participants should be done with caution. The present study excluded the analysis of the medial-lateral (ML) component of COM displacement, which is critical for postural stability. A previous study reported that a UCM analysis on the sagittal plane, 2D, kinematics revealed periods of both stabilising and destabilising synergies, a 3D UCM analysis of the COM kinematics instead consisted purely of stabilising synergies [7]. Candidate kinematic variables for the stabilisation of the ML-COM displacement may include the frontal plane angle of attack and leg length [38–40], as were used in this analysis. Determining ML-COM stabilising synergies is beyond the scope of this work but should be addressed in the future.

5. Conclusions

Two simple parameters from a spring-mass model, leg length and angle, were sufficient to stabilise the vertical COM displacement throughout the stance phase of running. Stabilisation of the vertical COM displacement occurred by harnessing the variability between leg length and angle. The same parameters were largely destabilising for the AP COM displacement, suggesting that to maintain constant running speed, the body may rely more on inter-limb variation to adjust the horizontal COM accelerations.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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