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Synergic control of vertical body oscillation during stance phase of treadmill running

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HIGHLIGHTS
- The Uncontrolled Manifold framework was used to study motor coordination in running.
- The vertical trajectory of the center of mass (COM_V) is stabilized in treadmill running stance phase.
- A multi-joint synergy (sagittal: hip, knee, and ankle; frontal: pelvis) is organized to stabilize COM_V.
- Running speed does not affect the multi-joint synergy stabilizing COM_V.

ABBREVIATIONS

COM_V	Vertical trajectory of the center of mass
CNS	Central nervous system
GRFv	Vertical ground reaction force
J	Jacobian matrix
SPM	Statistical parametric mapping
UCM	Uncontrolled Manifold
V_{UCM}	"Good" variance
V_{ORT}	"Bad" variance
ΔV	Synergy index
ΔV_Z	Modified Fisher z-transformation

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BACKGROUND: Stabilization of vertical body oscillation (i.e., vertical trajectory of the center of mass – COM_V) is critical for running efficiency and performance and may be influenced by running speed.
AIM: To investigate the presence of a multi-joint synergy that stabilizes COM_V during treadmill running and evaluate the effect of running speed on this synergy using the Uncontrolled Manifold (UCM) framework.
METHODS: Twenty-eight experienced runners (22–51 years old) ran on an instrumented treadmill at 2.5, 3.5, and 4.5 m/s. Ankle, knee, and hip angles (sagittal plane) and pelvis obliquity were used as elemental variables (DOF=4) to calculate the synergy index (ΔV_Z), the normalized difference between variance components in the joint space that did not affect (V_{UCM}) and those that did affect (V_{ORT}) vertical body oscillation (i.e., COM_V) during the stance phase (1-100%). Statistical parametric mapping (SPM) analysis was used to identify the presence of synergy and the influence of speed.
RESULTS: Across all speeds, a synergy (ΔV_Z>0) was present, except between 13% and 17% at the slowest speed. ΔV_Z was not affected by speed. While V_{ORT} remained unchanged across speeds, V_{UCM} was higher at the fastest speed between 7% and 43% of the stance phase.
INTERPRETATION: The findings indicate a robust multi-joint synergy that stabilizes vertical body oscillation during the stance phase of running. Although running speed did not disrupt this synergy, higher speeds were associated with increased “good” joint variability, suggesting enhanced flexibility of the motor control system without compromising stability of vertical body oscillation.

KEYWORDS: Center of mass | Coordination | Motor abundance | Uncontrolled manifold hypothesis | Synergy

INTRODUCTION

Running is a form of locomotion that enables individuals to move rapidly through space, though it demands higher energy expenditure compared to walking [1,2]. It relies on the cyclical and coordinated motion of multiple body segments [3]. According to the principle of motor abundance [4,5], the central nervous system (CNS) regulates and coordinates relevant motor elements (e.g., fingers, segments/joints, muscles) to stabilize one or more critical performance variables (e.g., total force, foot or center of mass trajectory, center of pressure) across a range of motor tasks (e.g., finger pressing task [6,7], walking/running [8–10], upright standing [11,12]). The ability of the CNS to stabilize important performance variables is crucial for motor performance, particularly when facing changes in external forces (e.g., ground reaction forces, external loads) or internal states (e.g., sensory feedback, joint stiffness, fatigue) [4]. A failure to achieve such stabilization can lead to inefficient movements, a higher risk of injury, reduced task success, and increased energetic cost, especially in tasks requiring precision, balance, or rapid adaptation to perturbations.

Vertical body oscillation, represented by the vertical trajectory of the center of mass (COM_V), is associated with running energy expenditure (i.e., running economy) and overall performance [13–16]. Therefore, it may represent an important performance variable that the CNS aims to stabilize. To investigate whether the CNS stabilizes COM_V during treadmill running, we employed the framework of Uncontrolled Manifold (UCM) hypothesis [17–19].

The UCM hypothesis proposes that the CNS organizes multi-element (e.g., multi-joint) synergies to stabilize one or more relevant performance variables (e.g., COM_V position) during the execution of a specific task (e.g., running). In this context, a *synergy* is defined as a neural organization that coordinates the actions of a series of elements relevant to the performance of a specific task, covarying these elements with the goal of stabilizing performance variables or measures [17–19]. To test the existence of such synergies, the variability across repeated trials (or cycles in continuous motor tasks like running) is estimated by the variance of all elemental variables directly involved in the task (e.g., joint angles, fingers, muscles) and is linked to the performance variable itself. Specifically, UCM analysis decomposes the total variance observed in the elemental variables into two distinct components. The first component, known as V_{UCM} or "good" variance, reflects combinations of elements that preserve the stability of the performance variable. The other component, V_{ORT} or "bad" variance, represents combinations among elements that result in performance errors or deviations from average performance across trials. If V_{UCM} is greater than V_{ORT}, it can be concluded that there is synergy controlling that performance variable. This results in a positive synergy index (ΔV). If ΔV is negative, meaning that V_{ORT} is greater than V_{UCM}, it can be concluded that the CNS is not actively involved in controlling that specific performance variable [17–19].

Previous studies by Möhler and collaborators [20–22] employed the UCM framework to investigate whether a multi-joint or multi-segmental synergy stabilizes the 2D (sagittal) and 3D COM trajectories during running. They also explored how running experience, speed, and fatigue affect this synergy and found evidence of robust multi-segmental synergies stabilizing the 2D and 3D COM trajectory throughout the running cycle. However, they did not observe any significant impact of experience, speed, and fatigue on the strength of these synergies. According to Möhler and colleagues [22], the limited sensitivity of UCM outcomes to detect potential effects of experience, speed, and fatigue may reflect the CNS's consistent and precise control over the joints contributing to the regulation of the hypothetical COM trajectory. However, Möhler and collaborators [20–22] did not investigate the COM stabilization along each individual axis of motion, focusing instead on the overall 3D trajectory. While informative, this approach may obscure the potential for axis-specific stabilization, as it is theoretically plausible that the CNS prioritizes COM stabilization in certain directions over others.

As previously mentioned, vertical body oscillation is closely linked to running efficiency and performance [13–16]. Yet, whether and how the CNS stabilizes COM_V through multi-joint coordination remains underexplored. Moreover, prior studies using the UCM approach have predominantly relied on complex 3D biomechanical models to estimate COM trajectory [20–24], which require detailed segmental anthropometrics and multiple assumptions to relate changes in the performance variable to the elemental variables (e.g., segmental angles). While these models provide adequate representations of 3D COM trajectory, they also introduce methodological challenges, such as increased sensitivity to marker placement errors, soft tissue movement artefact, and model assumptions [25,26]. In contrast, the approach adopted in this study employs a simpler linear model based on multiple regression analysis [9,27–29]. This method establishes a direct statistical relationship between the elemental variables (e.g., joint angles) and the performance variable (COM_V), without requiring detailed anthropometric modeling or assumptions about segment masses and inertias. As such, it offers a more accessible and robust framework for UCM analysis, facilitating broader application in experimental and clinical settings.

In the present study, we investigated the stabilization of COM_V trajectory in the stance phase during treadmill running and examined how this stabilization is influenced by running speed. Based upon the findings of Möhler and colleagues, who demonstrated that the COM trajectory is stabilized by a multi-segmental synergy during running [20–22], we hypothesized that the CNS would organize a multi-joint synergy to stabilize COM_V during the stance phase. Furthermore, considering that increased movement speed has been shown to disrupt motor coordination, reflected by greater 'bad' variance (V_{ORT}) and weaker synergies [36], we hypothesized that the strength of this synergy would be reduced at higher running speeds due to an increase in V_{ORT}.

METHODS

Participants

Kinematic and kinetic data were collected from 28 long-distance runners (27 males), aged 22 to 51 years (age, mean ± standard deviation: 34.75 ± 6.7 years). The data source is an openly accessible database (DOI: 10.6084/m9.figshare.4543435). Experienced runners, who had maintained a training schedule of at least three running sessions per week for an average of 8.4 (±7) years, were included in the study. Participants typically trained 3 to 5 times per week, covering over 20 km. The group's average running pace was 4.1 ± 0.4 min/km. This group of runners consisted of 3 elite and 25 competitive runners, who competed in races ranging from 5 km to marathons. Among the participants, 20 were right-foot dominant, and 8 were left-foot dominant. Detailed individual data are available at https://figshare.com/ndownloader/files/39452935.

On average, runners weighed 69.6 kg (± 7.7 kg) and were 175.9 cm (± 6.8 cm) tall. This study received approval from the Research Ethics Committee at the Federal University of ABC in Brazil (CAAE: 53063315.7.0000.5594). As reported by the authors, each participant read and signed an informed consent form before taking part in the study [30].

Study Protocol

The participants initially walked on a dual-belt, instrumented treadmill with embedded force plates (FIT; Bertec, Columbus, OH, USA) at 1.2 m/s for one minute to become familiar with the treadmill. They then stood on the left treadmill belt while the speed increased to 2.5 m/s. The participant ran at this speed for 3 minutes and 30 seconds, with kinematic and kinetic data recorded during the final 30 seconds. The treadmill speed was subsequently raised to 3.5 m/s, and the participant ran for another 3 minutes and 30 seconds, with data recorded in the last 30 seconds. This process was repeated at 4.5 m/s. According to the original authors, runners required three minutes to adapt to each treadmill speed before data recording.

Twelve Raptor4 cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) were used to record 48 technical and anatomical markers, some in clusters on the thigh and shank segments. After a 1-second standing calibration trial, most anatomical markers were removed. Kinematic data were recorded at 150 Hz, while the instrumented treadmill provided kinetic data recorded at 300 Hz. Each 30-second recording allowed for analysis of approximately 38, 40, and 43 cycles at 2.5, 3.5, and 4.5 m/s, respectively.

Data processing

We used a customized LabView routine (National Instruments, Austin, TX, USA) for data analysis. ASCII files with markers' 3D positions over time and force components from the left belt's embedded force plate were employed to compute the outcomes. We filtered all markers' data and the vertical force component using a 4th-order, zero-lag, Butterworth filter with a 10 Hz cutoff frequency. We estimated the vertical center of mass position (COM_V) from the virtual marker created at the midpoint of the markers placed on the right and left posterosuperior iliac spine [25,31]. The markers were also used to compute one segmental (i.e., pelvis obliquity) and three joint (i.e., hip, knee, and ankle in the sagittal plane) angles, following the method described by Fukuchi et al. [30]. The pelvis obliquity angle was expressed relative to the horizontal global coordinate plane and the joint angles expressed the distal segment movement relative to the proximal segment. Foot strike and toe-off events were identified based on the vertical ground reaction force (GRFv), with foot strike occurring when GRFv exceeded 20 N and toe off when it fell below this threshold [30]. To distinguish between left and right foot strikes, we analyzed the anterior-posterior position of the 5th metatarsal joint markers for both feet. The foot whose marker was positioned further forward at the moment of foot strike was the one in contact with the treadmill. Data analyses and UCM outcomes calculations were performed only for the dominant leg based on a previous study [32] and on a preliminary analysis of this dataset that showed no discernible differences between stance legs for any of the outcomes of interest.

UCM analysis of variance

The UCM analysis was performed to investigate how variations in four angles (i.e., ankle, knee, and hip angles in the sagittal plane, and pelvis obliquity) across running cycles influence COM_V during the stance phase of the running cycle. Initially, a multiple regression analysis was performed to model the relationship between the mean-free COM_V (dependent variable) and the mean-free values of the four angles (independent variables) throughout the stance phase [9,27–29]. From the resulting regression coefficients, a Jacobian matrix (***J***) was derived for each participant.

The mean-free joint angles were then time-normalized across the stance phase from 1-100%. At each time point, the mean-free joint angle vectors were projected into the null space (UCM) and the orthogonal space of ***J***, using matrix decomposition. The total variance of the projected joint configuration was partitioned at each instant into two components: (1) V_{UCM}, the variance within the null space of ***J*** that does not affect COM_V, and (2) V_{ORT}, the variance in the orthogonal space that affects COM_V.

With V_{UCM} and V_{ORT} calculated for each instant, ΔV was computed at each time point as $\Delta V=(V_{UCM}/3-V_{ORT}/1)/(V_{TOT}/4)$, where V_{TOT} represents the total variance. Normalization by the dimensionality of the corresponding space was applied to V_{UCM}, V_{ORT}, and V_{TOT}. Since ΔV does not follow a normal distribution, a modified Fisher z transformation was used for normalization, [$\Delta V_Z=(0.5\times\ln((4+\Delta V)/(1.333-\Delta V))) - 0.549$], where ln represents the natural log and the constants represent the absolute boundaries of ΔV (−4 to 1.333) and the z-transformed value when ΔV = 0 (i.e., 0.549). Positive values of ΔV_Z indicate the presence of multi-joint synergy stabilizing COM_V during the stance phase, with larger values reflecting stronger synergies.

Statistical Analysis

Statistical parametric mapping (SPM) analyses [33] were employed to test the hypothesis of the study. Three one-sample t-test SPM analyses, one for each running speed, were performed to test whether ΔV_Z was significantly greater than zero, which would indicate the presence of a multi-joint synergy stabilizing COM_V. In addition, F-test SPM analyses were conducted to examine the effect of running speed on ΔV_Z, V_{UCM}, and V_{ORT}. When significant effects were found, post-hoc SPM t-tests were performed. Because V_{UCM} and V_{ORT} were not normally distributed, they were log-transformed prior to the SPM analyses. The significance level was set at 0.05 for all tests.

RESULTS

The COM_V position, normalized by the participants' stature, ranged from 0.45 to 0.63 (Figure 1) during the stance phase, reaching its minimum height at 41.2% (±2.8), 42.6% (±2.3), and 43.3% (±2.7) of the stance phase for 2.5, 3.5, and 4.5 m/s, respectively.

The SPM F-test revealed a significant effect of speed on COM_V across a substantial portion of the stance phase [1-29% (SPM{F}, $F_{(2,54)} = 521$, $p < 0.001$, critical threshold = 3.91) and 50-100% (SPM{F}, $F_{(2,54)} = 810$, $p < 0.001$, critical threshold = 3.91)] but not in the moments near the COM_V change of direction (30-49%, SPM{F}, $F_{(2,54)} = 3.7$, $p > 0.05$, critical threshold = 3.91).

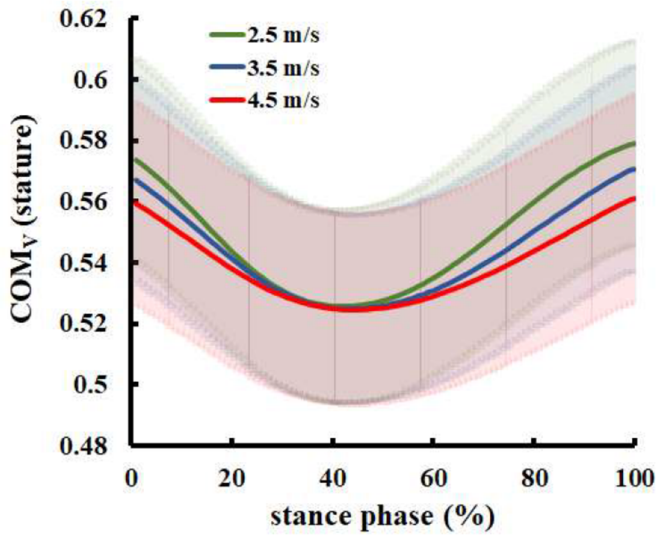

Figure 1. Across-subject averaged COM_V (normalized by stature) trajectories during the running stance phase (1-100%) in the 2.5 m/s (green line), 3.5 m/s (blue line), and 4.5 m/s (red line) speed conditions. Error bars represent standard error for each point in the stance phase (1-100%).

The multiple linear regression analyses used to determine ***J*** revealed high coefficients of determination ($R^2 \geq 0.9$ for all cases, median $R^2 \geq 0.98$, across speed conditions). This indicates that the model incorporating the four angles effectively predicted COM_V at all speeds. Additionally, all four angles significantly contributed to the model ($p < 0.05$).

The one-sample SPM{t} analyses revealed that ΔV_Z was consistently greater than zero throughout the stance phase in all three speed conditions (Figure 2A), except for a brief interval between 13-17% in the 2.5 m/s condition (Figure 2B-D). Additionally, the SPM F-test indicated a significant main effect of speed on ΔV_Z only by the end of the stance phase (98-100%, SPM{F}, $F_{(2,54)} = 5.95$, $p = 0.049$, critical threshold = 5.18, Fig. 3A). However, post-hoc pairwise comparisons (SPM t-test) revealed no significant differences between speed conditions for ΔV_Z (all $p > 0.05$, Figure 3B-D).

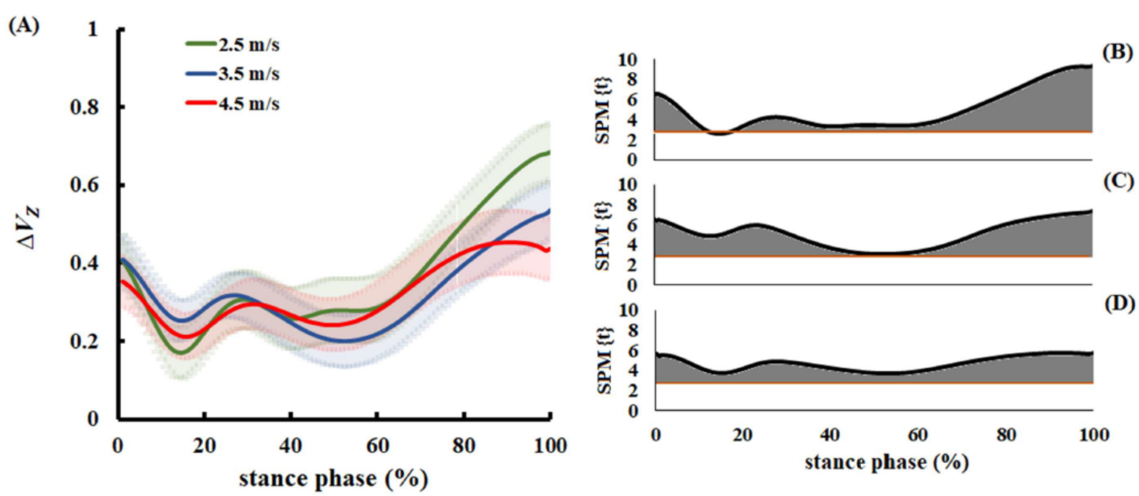

Figure 2. Across-subject averaged synergy index (ΔV_Z) time-series at speeds of 2.5 m/s (green line), 3.5 m/s (blue line), and 4.5 m/s (red line) with error bars representing standard error for each point in the stance phase (A, left-hand side). The plots on the right-hand side (B-D) show one-sample SPM {t} trajectories during the running stance phase (1-100%) for each tested speed: (B) 2.5 m/s, (C) 3.5 m/s, and (D) 4.5 m/s. Horizontal lines in B, C, and D represent t-critical values. Gray areas in B, C, and D indicate intervals with p < 0.05.

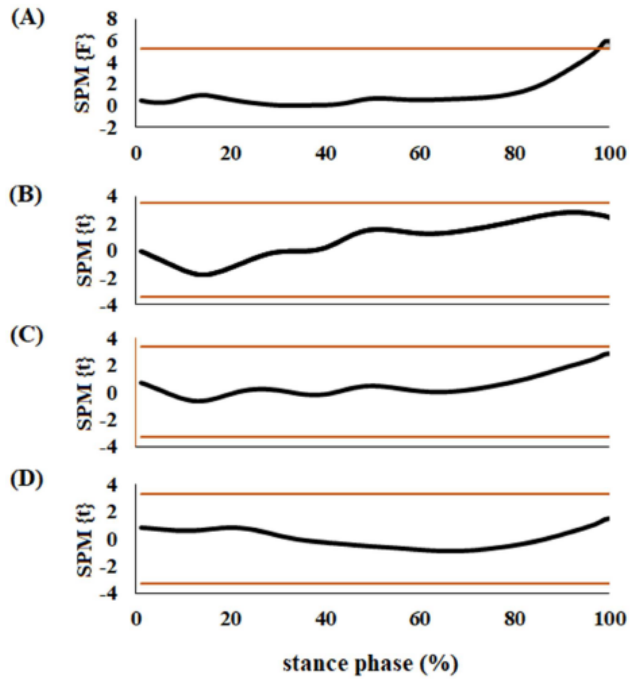

Figure 3. SPM {F} (A) and post-hot SPM t-tests (B-D) values during the running stance phase for the synergy index (ΔV_Z). B: 2.5 m/s vs. 3.5 m/s comparison; C: 2.5 m/s vs. 4.5 m/s comparison; and D: 3.5 m/s vs. 4.5 m/s comparison. Horizontal lines represent the F-critical (A) and t-critical (B-D) values.

The SPM analysis revealed a significant effect of speed on V_{UCM} (log-transformed, Figure 4A) during an interval between 7% and 43% of the stance phase (Figure 4B, SPM{F}, $F_{(2,54)} = 14.46$, $p = 0.002$, critical threshold = 5.29). Specifically, V_{UCM} was larger at 4.5 m/s compared to 2.5 between 10% and 41% of the stance phase (SPM{t}, $t_{27} = 5.02$, $p < 0.001$, critical threshold = 3.42, Figure 4D) and larger at 4.5 m/s compared to 3.5 m/s between 36% and 43% (SPM{t}, $t_{27} = 3.57$, $p = 0.013$, critical threshold = 3.4, Figure 4E) running speed. In contrast, for V_{ORT} (log-transformed, Figure 5A), the SPM analysis did not reveal a significant effect of speed (SPM{F}, $F_{(2,54)} = 4.07$, $p > 0.05$, critical threshold = 5.03, Figure 5B).

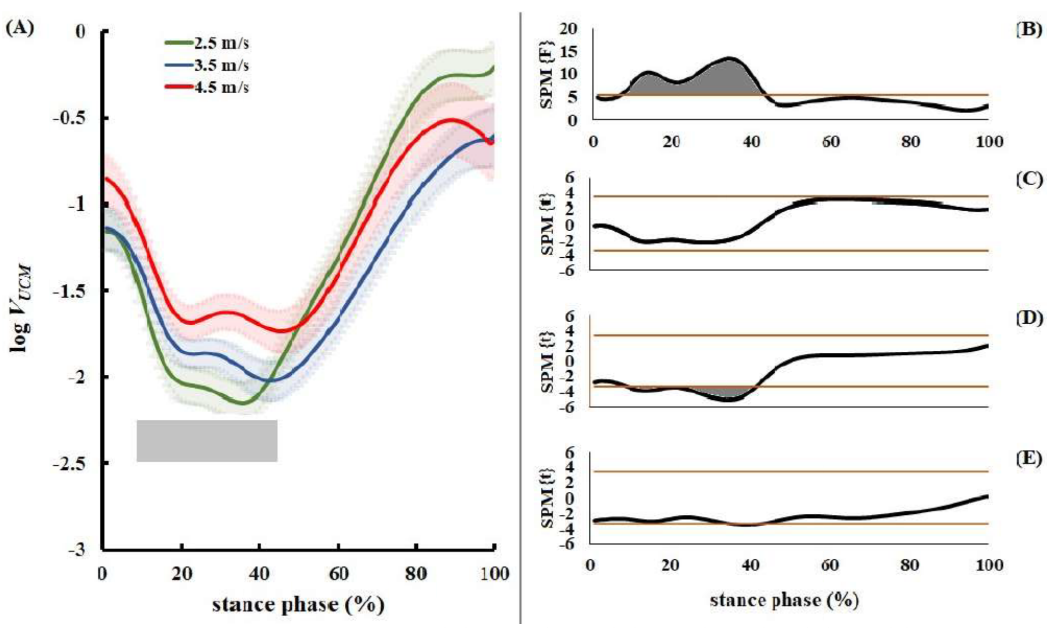

Figure 4. Across-subject averaged V_{UCM} time-series at speeds of 2.5 m/s (green line), 3.5 m/s (blue line), and 4.5 m/s (red line) (A, left-hand side). (B) SPM one-way ANOVA results [SPM {F}] testing the effect of speed on V_{UCM}. SPM t-test results for the following comparisons: (C) 2.5 m/s and 3.5 m/s, (D) 2.5 m/s and 4.5 m/s, and (E) 3.5 m/s and 4.5 m/s condition. Error bars in (A) represent standard error. The horizontal line in (B) is the SPM F-critical and the horizontal lines in C, D, and E are SPM t-critical values. Horizontal gray areas represent intervals where p<0.05 for the SMP F-test.

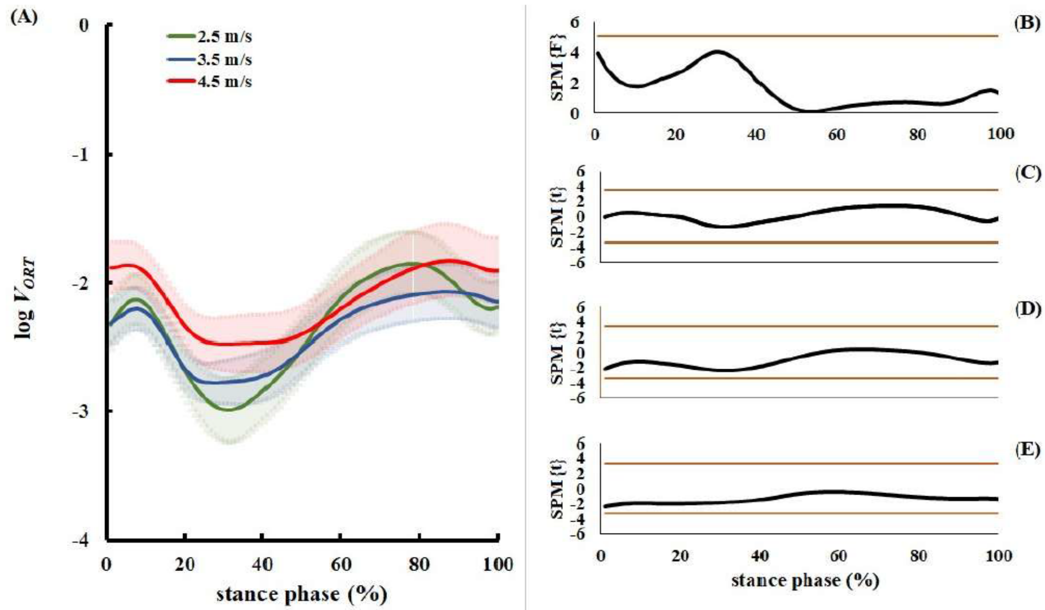

Figure 5. Across-subject averaged V_{ORT} time-series at speeds of 2.5 m/s (green line), 3.5 m/s (blue line), and 4.5 m/s (red line) (A, left-hand side). (B) SMP one-way ANOVA results [SPM {F}] testing the effect of speed on V_{UCM}. SMP t-test results for the following comparisons: (C) 2.5 m/s and 3.5 m/s, (D) 2.5 m/s and 4.5 m/s, and (E) 3.5 m/s and 4.5 m/s condition. Error bars in (A) represent standard error. The horizontal line in (B) is the SPM F-critical and the horizontal lines in C, D, and E are SPM t-critical values.

DISCUSSION

In this study, we tested two hypotheses: (1) that a multi-joint synergy would stabilize vertical body oscillation during the stance phase of treadmill running, and (2) that this synergy would weaken with increasing running speed. Our findings confirmed the first hypothesis but refuted the second. We observed the presence of a multi-joint synergy (ΔV_Z) responsible for stabilizing the COM_V (i.e., body vertical oscillation) throughout the stance phase. Additionally, we found that vertical body oscillation was affected by running speed at the onset and end of the stance phase but remained stable at its minimum point—when the trajectory reverses from descending to ascending. Moreover, running speed influenced the 'good' variance component, V_{UCM}, primarily in the early stance phase, from just after touchdown until the COM_V changed direction. Specifically, V_{UCM} was highest in the fastest speed condition within this interval. In contrast, the bad variance (V_{ORT}) was not impacted by running speed.

Previous studies by Mohler and colleagues [20–22] showed that the planar and tridimensional trajectory of the COM is stabilized during running. However, they did not analyze the stabilization of each axis independently, leaving open the question of how much of this stabilization is specifically related to vertical body oscillation. Most recently, Liew and collaborators [34], using the same dataset as the present study, showed that the COM_V stability can be achieved through covariation between two parameters from a simple spring-mass model: leg angle (i.e., the angle between the leg vector and the horizontal surface) and leg length. They applied the UCM concept but rather than using elemental variables typically considered to be directly controlled by the CNS (e.g., joint or segmental angles), they treated the covariation between two performance variables (leg angle and leg length), which were presumed to be already stabilized by the CNS, to maintain the stability of a third performance variable: the vertical (or the horizontal) COM trajectory. Their results suggested the existence of a covariation pattern between leg angle and leg length that stabilized vertical, but not horizontal, COM trajectories during running stance, particularly at the beginning and end of this phase.

Our study is the first to demonstrate that COM_V is stabilized by a multi-joint synergy based on elemental variables that are more mechanistically tied to the neural control of movement. Unlike Liew and collaborators [34], who used leg angle and leg length (i.e., parameters that are the result of coordinated actions of multiple joints), we utilized individual joint angles in the sagittal and frontal planes as elemental variables. These angles directly and independently contribute to the vertical displacement of the COM: greater flexion leads to a lower COM_V while greater extension results in a higher COM_V. Importantly, these elemental variables are under direct and independent control by the CNS, as each joint can be actively modulated by specific muscle groups with distinct neural control [35]. This provides a more mechanistically grounded model to analyze motor synergies compared to composite variables such as leg length or angle, which are emergent outcomes rather than directly controlled elements. Thus, our findings provide stronger evidence that the CNS forms synergies at the joint level to stabilize vertical body oscillation—a variable known to be critical for running economy [13–16] and performance.

The notion that vertical body oscillation is tightly controlled by the CNS is further supported by the finding that COM_V

displacement at its minimum point is unaffected by running speed. Additionally, the stability of the synergy index (ΔV_Z) and the lack of change in V_{ORT} across speeds suggest that the CNS consistently prioritizes control of COM_V regardless of locomotor demand. In contrast to general expectations that increasing speed disrupts motor coordination, reflected by higher 'bad' variance (V_{ORT}) and weaker synergies [36], our results indicate that the CNS maintains tight control over COM_V, likely due to its biomechanical and metabolic relevance.

Fukuchi and collaborators, using the same dataset, reported substantial changes in several biomechanical variables across speeds, including stride length and cadence, joint angles, ground reaction forces, torques, and power [30]. Additionally, our data show that vertical body oscillation (i.e., COM_V trajectory) was influenced by running speed, with higher COM_V values observed at slower speeds during both the initial and latter portions of the stance phase (see Fig. 1). However, despite these biomechanical differences, increased running speed did not impair COM_V stability. The first indication that vertical body oscillation is tightly controlled by the CNS, as suggested by Möhler and colleagues [22], is the lack of effect of speed in the COM_V displacement during the phase when the COM_V changes direction from descending to ascending. The second indication is that both the bad variance (i.e., V_{ORT}) and the index of multi-joint synergy stabilizing the COM_V are not affected by speed at any time during the stance phase.

In general, the movement speed influences control, with faster speeds often leading to decreased task performance, increased 'bad' variance among elemental variables, and reduced synergy strength [36]. However, our findings do not support this assumption. Mohler and collaborators [21] tested the stability of the 3D COM trajectory using the UCM approach in novice and experienced runners. The participants ran at two different speeds, 10 and 15 km/h, and they observed no differences in the synergy index between groups at both speeds. Although they did not test the effect of running speed on the synergy index, examining their reported values (Table II in Möhler and colleagues [21]) suggests that the effect of speed is negligible or non-existent. Conversely, our results are partially consistent with those of Liew and collaborators [34] who, using the same dataset and investigating the stabilization of the COM_V through the covariation of leg angle and leg length, found that the index of motor abundance (IMA), which is similar to our synergy index, was affected by running speed in certain parts of the stance phase (onset, near midstance, and at the end). However, those researchers did not provide a plausible explanation for the observed effect of speed. It is important to note that although the performance variable was the same (i.e., COM_V), the elemental variables differed between our study and that of Liew and collaborators [34].

Interestingly, while V_{ORT} and ΔV_Z were not influenced by running speed, we did find an effect of speed on V_{UCM}. Specifically, V_{UCM} was greater in the fastest speed condition (4.5 m/s) compared to the slowest (2.5 m/s) between 7% and 43% of the stance phase, which corresponds to the braking phase, with 43% mark aligning with the point at which COM_V transitions from descending to ascending. This period is dedicated to absorbing impact forces and controlling the descent of the body through eccentric action of the hip and knee extensors and ankle dorsiflexors [37,38]. V_{UCM} represents the trial-by-trial multi-joint variability that does not interfere with task performance (i.e., COM_V) and is linked to the CNS's flexibility and adaptability in finding proper joint motion combinations to respond promptly to perturbations [39–41]. Thus, higher V_{UCM} at faster speeds likely represents increased flexibility in joint coordination, allowing the CNS to prepare for and respond to perturbations within a shorter time frame, primarily during the running braking phase. Notably, regardless of running speed both V_{UCM} and V_{ORT} are close to their minimum values near the moment of COM_V reversal, suggesting that the CNS transiently reduces multi-joint variability to avoid further downward COM displacement and potential collapse.

The importance of UCM analysis to improving running performance lies in its ability to identify how the CNS organizes joint coordination to stabilize salient performance variables such as COM_V. Understanding the structure and strength of motor synergies can guide coaches and clinicians in designing training protocols that enhance flexibility without compromising stability. For instance, a runner exhibiting low V_{UCM} in early stance may lack the adaptive capacity to respond to perturbations at higher speeds, under fatigue, or when running on uneven terrain. Conversely, excessive V_{ORT} may indicate poor joint coordination and ineffective movement patterns. By targeting specific joints or phases of stance where synergy is weak, interventions can be developed to improve running control and economy. Moreover, UCM-based indices may serve as biomarkers to assess motor competence, track training progress, or monitor recovery in rehabilitation contexts.

This study has limitations that should be acknowledged. Some may argue that treadmill running differs from overground running and could influence coordination patterns. However, studies focusing on joint angles and COM trajectory suggest that the differences between treadmill and overground running are minimal [42,43]. Despite these minimal differences, future studies should test the generalizability of these results to overground running. Another potential limitation is that the vertical trajectory of the COM was not based on the actual COM position obtained with a full-body biomechanical model but on a virtual marker positioned between the posterior superior iliac spine markers. However, earlier studies have shown that the vertical trajectory of this virtual marker closely matches the vertical displacement of the COM calculated using a full-body biomechanical model [25,31]. Additionally, as mentioned by Liew and collaborators [34], since this dataset predominantly includes male participants, it is important to exercise caution when extrapolating our findings to female participants. Finally, although studies indicate consistent biomechanics in well-trained runners up to the age of 60 [44,45], the relatively broad age range of our sample (22–51 years) may introduce some age-related variability. Therefore, the age range of the sample should be considered a potential limitation of our study.

Despite these considerations, this study represents a pioneering investigation into how the joints of the lower limbs and pelvis coordinate to stabilize vertical body oscillation during the running stance phase. Further research would be valuable in sports and rehabilitation science to examine how acute factors (e.g., central and peripheral fatigue) and chronic conditions (e.g., patellofemoral pain syndrome, low back pain) may impact the multi-joint synergy involved in stabilizing salient performance variables during running, and how interventions might enhance this coordination.

CONCLUSION

In conclusion, the findings indicated that the CNS organizes a multi-joint synergy to stabilize vertical body oscillation (i.e., COM_V) throughout most of the running stance phase. This stabilization plays a crucial role in running performance and economy. Excessive downward oscillation of the body would require greater eccentric muscle torque to prevent collapse, while excessive upward movement at the beginning and end of the stance phase could suggest that the generated muscle torque is not being efficiently directed toward forward propulsion, which is the primary goal of running. The absence of a speed effect on COM_V further suggests that vertical body oscillation is tightly regulated by the CNS, regardless of external conditions. However, the greater good variance (V_{UCM}) in the fastest condition at the first half of the stance phase, when the COM is descending and approaching its lowest position indicates that the CNS is better prepared to deal with extreme conditions by increasing the system´s flexibility.

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