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Ankle exoskeleton assistance increases task-relevant variability without altering center of mass control during walking

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ABSTRACT

Background: Ankle exoskeletons alter joint kinematics during walking, yet their effects on whole-body coordination remain unclear. This study investigated how ankle exoskeleton assistance influences the structure of motor variability and center-of-mass movement during steady-state walking.
Methods: Twenty healthy adults walked on a treadmill at 1.1 m/s without the exoskeleton (noExo) and with active exoskeleton assistance (Exo). Whole-body kinematics were recorded. Variability was analyzed using the Uncontrolled Manifold (UCM) approach. Joint angle variability was decomposed into components that do not affect center-of-mass position ($UCM_{||}$) and components that do ($UCM_{\perp}$). Their ratio (UCM_{ratio}), reflecting the synergy stabilizing the center-of-mass, was calculated. Center-of-mass position was analyzed separately in three dimensions. Time-continuous differences across the gait cycle were evaluated using statistical parametric mapping.
Results: $UCM_{||}$ and UCM_{ratio} showed no significant differences between conditions. $UCM_{\perp}$ was higher with exoskeleton assistance over large portions of the gait cycle (0–80%, $p = 0.001$; 91–100%, $p = 0.022$). Center-of-mass movement in the mediolateral and anteroposterior directions did not differ between conditions, while small differences were observed in the vertical direction (higher in Exo at 23–31% and 75–84%, $p = 0.037$; lower at 48–54%, $p = 0.042$).
Conclusion: Ankle exoskeleton assistance increased joint-level variability affecting center-of-mass movement, but overall center-of-mass control was preserved, with only small changes in vertical center-of-mass displacement. Healthy adults maintained whole-body coordination despite altered mechanical conditions introduced by the exoskeleton. These findings are relevant for clinical exoskeleton use, where assistive devices should support walking without compromising center-of-mass control and balance.

1. Introduction

Ankle exoskeletons have emerged as a promising assistive technology to support or restore human locomotion across a range of applications, including rehabilitation, mobility assistance, and performance enhancement [1,2]. Ankle exoskeletons can provide external plantarflexion torque and have been shown to reduce the net metabolic cost of walking in both healthy individuals and clinical populations, such as those with stroke or spinal cord injury [3–6]. Due to their relatively compact mechanical design and direct interaction with a key joint involved in propulsion, ankle exoskeletons have been suggested as an efficient alternative to more complex multi-joint systems [5,7,8]. However, despite their increasing use, neuromechanical adaptations induced by such assistance remain poorly understood, particularly in relation to motor control strategies and gait stability [9,10].

In this context, previous research has investigated the effects of ankle exoskeletons under both perturbed and steady-state walking conditions, often focusing on metabolic cost and adaptations in spatiotemporal, kinematic, and muscular variables [3,4,11,12]. While several studies have examined steady-state walking with ankle exoskeletons, these have primarily focused on average outcome measures [3,7,8,13], rather than whole-body coordination and the underlying organization of motor

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control. As a result, how ankle exoskeleton assistance influences coordination across body segments remains insufficiently understood. Importantly, analyses based solely on average measures do not capture the structure of motor variability, which has been shown to reflect the underlying organization of motor control [14–16]. Therefore, it remains unclear how exoskeleton-induced changes affect the structure of motor variability and its role in gait stability.

In line with this, our previous work showed that ankle exoskeleton assistance alters gait control across multiple levels during steady walking [17]. Specifically, walking with the exoskeleton increased stride-to-stride spatiotemporal variability and reduced stance ratio, while mean stride length, mean step width, and global gait stability did not differ between conditions. At the same time, local dynamic stability increased at distal segments, suggesting increased local dynamic stability at segments close to the assisted ankle joint. These findings indicate that exoskeleton assistance induced measurable adaptations in gait control while global gait stability was preserved. However, they do not explain whether exoskeleton assistance alters how motor variability is organized across joint degrees-of-freedom, particularly with respect to whole-body center-of-mass control. Since the center-of-mass is widely considered a critical variable for maintaining stability during locomotion [18,19] and has frequently been considered as a task-relevant performance variable in motor control and gait studies [20–23], center-of-mass control during treadmill walking should not be interpreted only as staying centered on the treadmill, but also as the whole-body coordination required to stabilize center-of-mass across gait cycles. Therefore, it is important to determine whether ankle-level assistance alters how joint-level variability is organized with respect to center-of-mass control.

Importantly, variability in motor behavior is not inherently detrimental; rather, its functional role depends on its structure and magnitude [15,24]. Increased variability may reflect either impaired control or flexible coordination strategies that preserve task performance [15]. To address this issue, frameworks that go beyond scalar measures of variability are required. One such approach is the Uncontrolled Manifold (UCM), which provides a method to decompose variability in elemental variables (e.g., joint angles) into components that do and do not affect a performance variable [20,24]. Within this framework, variability is partitioned into components parallel to the uncontrolled space ($\mathrm{UCM}_{||}$), which preserves the performance variable, and orthogonal to it ($\mathrm{UCM}_{\perp}$), which leads to performance errors. Greater variability within the UCM relative to the orthogonal subspace ($\mathrm{UCM}_{\mathrm{ratio}}$) is interpreted as evidence of a synergy stabilizing the performance variable. Thus, the UCM approach enables a deeper understanding of how the central nervous system organizes redundancy to stabilize task-relevant variables such as the center-of-mass during movement.

Based on this framework, the present study aimed to investigate whether active ankle exoskeleton assistance alters the organization of joint-level variability with respect to center-of-mass control during steady-state walking. Using the UCM approach, kinematic variability in joint space was analyzed, with the center-of-mass defined as the performance variable. It was hypothesized that exoskeleton assistance would lead to an increase in $\mathrm{UCM}_{||}$ (i.e., the component that does not affect center-of-mass position), reflecting enhanced flexibility in coordinating joint movements while preserving center-of-mass stability. Consequently, an increase in $\mathrm{UCM}_{\mathrm{ratio}}$ was also expected, driven by elevated parallel variability without a corresponding increase in $\mathrm{UCM}_{\perp}$. Such changes would indicate improved stabilization of the center-of-mass despite increased variability in the elemental variables (i.e. joint angles). In addition, it was hypothesized that center-of-mass kinematics would remain unchanged between conditions, reflecting the preservation of overall whole-body movement despite changes in the joint-level variability.

2. Methods

2.1. Sample

The sample size was determined *a priori* based on previous local dynamic stability outcomes [25] using a one-sided paired *t*-test ($\alpha = 0.05$, power = 0.90) in G*Power (V3.1.9.7), which indicated a required sample size of 17 participants. To ensure sufficient statistical power and reliable estimation of variability-based measures, twenty healthy adults were included (female n = 6, age: 24.6 ± 3.0 years; height: 1.79 ± 0.07 m; body mass: 71.7 ± 9.5 kg). All participants were free from neurological or musculoskeletal disorders. The present study is based on a previously collected dataset [17]; however, the current analysis focuses on the structure of motor variability using a UCM approach. All participants provided written informed consent prior to participation. The study protocol was approved by the ethics committee of the Karlsruhe Institute of Technology.

2.2. Exoskeleton

The ankle exoskeleton has been described in detail previously [17]; key aspects are summarized here for clarity (Fig. 1). A bilateral ankle exoskeleton, adapted from a previously described design [26], was used to provide plantarflexion assistance during walking. The device consisted of a rigid frame with shank and foot segments connected via a multi-joint linkage that allows three ankle degrees-of-freedom. Dorsiflexion, inversion/eversion, and internal/external rotation were implemented as passive degrees-of-freedom, whereas plantarflexion was actively actuated through a cable-driven system. The exoskeleton was adjustable to accommodate a range of shoe sizes and lower-leg geometries. A central actuation unit was mounted close to the body and its center-of-mass via a hip belt to reduce its impact on the user's natural movements. The total mass of the system was distributed between the bilateral units (1.2 kg per side) and the central actuator (3.3 kg). Assistive torque was applied during push-off (terminal stance and pre-swing) using subject-specific torque profiles derived from previously reported optimal assistance patterns [27]. The target peak plantarflexion assistance was initially set to 20 Nm per ankle and was not scaled to individual body mass. However, for four of the 18 participants, a lower peak torque was applied because of technical issues or because the participant could not comfortably adapt to the higher assistance level. Across participants, the applied peak torque was 16.7 ± 5.8 Nm, corresponding to 0.24 ± 0.09 Nm/kg when normalized to body mass. Gait events were detected using insole-embedded force-sensitive resistors, and the timing of assistance was updated based on the preceding gait

Fig. 1. Bilateral ankle exoskeleton used in this study. The device comprises rigid shank and foot segments connected via a multi-joint linkage enabling three ankle degrees-of-freedom. Plantarflexion is actively actuated through a cable-driven mechanism, while dorsiflexion, inversion/eversion, and internal/external rotation remain passive.

cycles.

2.3. Study design

The experimental protocol was part of a larger study and has been described previously [17]; only procedures relevant to the present analysis are summarized here. Complementary gait-related outcomes from the same protocol have been reported separately [17]. Participants walked on a split-belt treadmill (M-Gait, Motek Medical, Amsterdam, The Netherlands) at a constant speed of 1.1 m/s while secured with a safety harness that did not provide body-weight support. Following a standardized warm-up period of 5 min without exoskeleton, participants completed walking trials under two conditions: walking without wearing the exoskeleton (noExo) and walking with active exoskeleton assistance (Exo). Conditions were applied in a randomized, counterbalanced crossover design. In the Exo condition, participants first completed a 10-minute familiarization period to allow adaptation to the device, followed by a post-familiarization 3-minute walking trial used for analysis. In the noExo condition, participants completed a 3-minute walking trial without assistance. When the noExo condition followed the Exo condition, a 5-minute de-adaptation period and an additional rest period were included prior to data collection.

2.4. Data acquisition and preprocessing

Whole-body kinematic data were collected using a 16-camera motion capture system (Vicon Motion Systems, Oxford, UK) at a sampling rate of 200 Hz and 61 reflective markers [17]. Marker trajectories were labeled and reconstructed in Vicon Nexus (version 2.15) and subsequently processed in MATLAB (R2024a; MathWorks Inc., Natick, MA, USA). Prior to analysis, kinematic data were filtered using a fourth-order low-pass Butterworth filter with a cutoff frequency of 10 Hz. Inverse kinematics was performed using the RajagopalLaiUhlrich2023 OpenSim model (SimTK, Stanford University, USA) to obtain joint angles. A subset of 47 markers was used for scaling and inverse kinematics. The generic model was scaled to each participant based on a static standing trial using the OpenSim scaling tool. Scaling was iteratively adjusted until marker errors were within recommended limits (maximum error $<$ 2 cm; root-mean-square error $<$ 1 cm).

2.5. Uncontrolled manifold analysis

To investigate the structure of motor variability, a UCM analysis was conducted [20]. Joint angles were defined as elemental variables (25 °-of-freedom), and the three-dimensional position of the center-of-mass was defined as the performance variable (3 °-of-freedom), such that the UCM analysis was performed with respect to the combined three-dimensional center-of-mass. A participant-specific anthropometric full-body model was used to relate joint configurations to center-of-mass position [23]. This model is based on established body-segment geometry and has been used in previous UCM studies of locomotion [21,23,28]. The center-of-mass was computed as the weighted sum of segments (Eq. 1), where N denotes the number of body segments ($N = 15$), V_m the volume of segment m, and r_m its center-of-gravity vector.

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

For each time-normalized gait cycle, a mean joint configuration θ^0, was calculated, and deviations from this mean were obtained for each stride. The relationship between joint angles and center-of-mass position was linearized around the mean configuration using the Jacobian matrix $J(\theta^0)$. The null space of the Jacobian spanned basis vectors ε_i defines the uncontrolled space (Eq. 2).

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

Based on this linearization, deviations in joint space $(\theta - \theta^0)$ were projected onto the null space to obtain its parallel, $\theta_{\parallel}$ (Eq. 3), and orthogonal, $\theta_{\perp}$ (Eq. 4) components.

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

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

Variability parallel to the uncontrolled space ($UCM_{||}$, Eq. 5) and orthogonal to it ($UCM_{\perp}$; Eq. 6) were computed. Thereby, $UCM_{||}$ reflects combinations of joint angle variations that do not affect the center-of-mass position and is interpreted as variability that preserves the performance variable, whereas $UCM_{\perp}$ represents variability that leads to changes in center-of-mass position and thus affects task performance.

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

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

In addition, the UCM_{ratio} was calculated to quantify the relative contribution of variability that stabilizes the center-of-mass (Eq. 7). A UCM_{ratio} greater than zero indicates the presence of a synergy stabilizing the center-of-mass, with higher values reflecting stronger stabilization. All UCM components were calculated across the gait cycle for each participant and condition.

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

2.6. Statistical analysis

Statistical analyses were performed to compare the Exo and noExo conditions for all outcome variables, including $UCM_{||}$, $UCM_{\perp}$, UCM_{ratio}, and center-of-mass position. UCM variables were derived with respect to the three-dimensional center-of-mass, whereas center-of-mass position was additionally analyzed separately for each dimension (mediolateral, COM_{ML}; anteroposterior, COM_{AP}; vertical, COM_{VER}). Time-continuous differences across the gait cycle were assessed using one-dimensional statistical parametric mapping (SPM) paired *t*-tests (spm1d toolbox, MATLAB). Additionally, UCM_{ratio} was tested against zero for both Exo and noExo conditions using one-sample SPM *t*-tests to assess the presence of a stabilizing synergy. All variables were time-normalized to 101 data points representing the full stride. Only left strides were analyzed, as symmetry between limbs was demonstrated in a previous study [17]. Prior to hypothesis testing, normality of the residuals was evaluated using SPM normality tests. If the assumption of normality was violated, a non-parametric equivalent test was applied using permutation-based inference (1000 iterations). Thus, potential non-normality was addressed statistically rather than by applying a general log transformation. Otherwise, parametric paired *t*-tests were conducted. The significance level was set to $\alpha = 0.05$. Significant clusters were identified across the gait cycle, and corresponding p-values were reported.

3. Results

$UCM_{||}$ showed no differences between conditions over the gait cycle (Fig. 2, left column). In contrast, $UCM_{\perp}$ revealed condition-dependent differences (Fig. 2, middle column), with higher values in the Exo compared to the noExo condition over a large portion of the gait cycle (0–80%, $p = 0.001$, and 91–100%, $p = 0.022$). UCM_{ratio} was greater than zero across the entire stride (0–100%, $p < 0.001$) in both Exo and

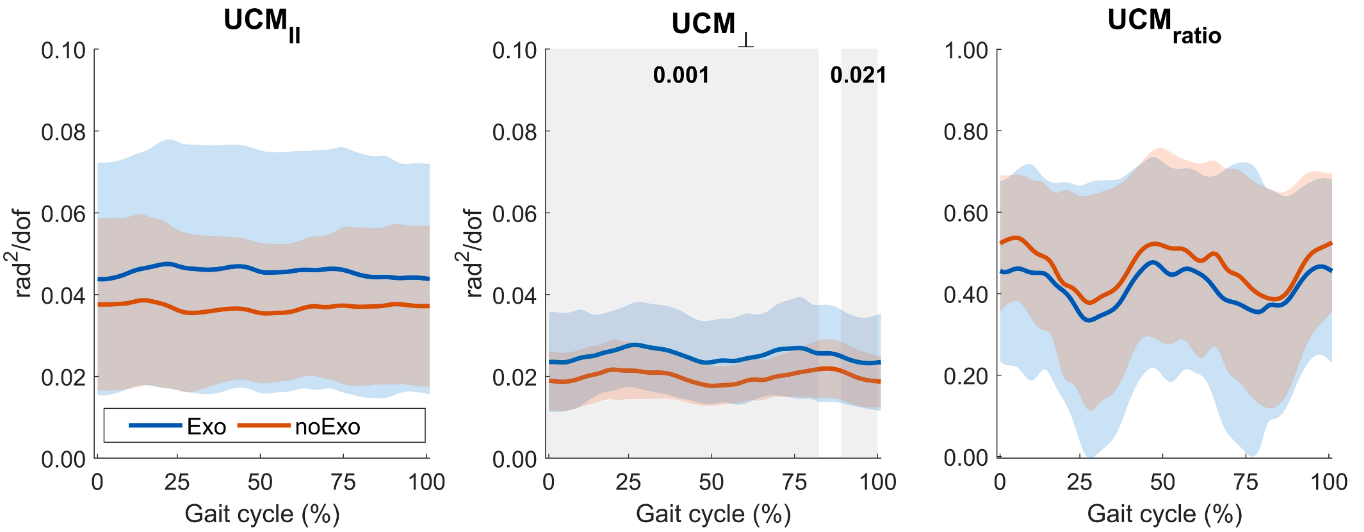

Fig. 2. UCM components (UCM$_{||}$, UCM$_{\perp}$, UCM$_{ratio}$) across the gait cycle for the exoskeleton (Exo, blue) and without exoskeleton (noExo, orange) conditions. Colored shaded areas represent inter-subject variability (± standard deviation). Grey shaded regions indicate significant clusters reflecting differences between Exo and noExo conditions. Corresponding cluster-level p-values are displayed above the shaded regions.

noExo conditions. However, no significant differences between conditions were observed for UCM$_{ratio}$ (Fig. 2, right column).

COM$_{ML}$ and COM$_{AP}$ showed no differences between conditions across the gait cycle (Fig. 3, left and middle columns). In contrast, COM$_{VER}$ showed condition-dependent differences (Fig. 3, right column) with slightly higher values in the Exo condition during two phases of the gait cycle (23–31%, and 75–84%, $p = 0.037$), and lower values during an intermediate phase (48–54%, $p = 0.042$).

4. Discussion

This study aimed to investigate how an actuated ankle exoskeleton influences the coordination of joint variability with respect to center-of-mass control and kinematics compared with walking without the exoskeleton during steady walking. The results showed that joint-angle variability that preserved center-of-mass position did not differ between conditions. In contrast, joint-angle variability that affected center-of-mass position was increased when walking with the exoskeleton, reflecting greater variability affecting center-of-mass position. However, the ratio between the two variability components remained unchanged, suggesting that the relative structure of variability and thus the synergy stabilizing the center-of-mass was maintained. At the kinematic level, center-of-mass movement in the mediolateral and anteroposterior directions remained unchanged, while small but significant differences were observed in vertical center-of-mass displacement.

4.1. Unchanged synergy structure despite increased variability affecting center of mass

Contrary to the expectation that exoskeleton assistance would alter the structure of motor variability, the present findings indicate that the coordination of joint variability stabilizing the center-of-mass was preserved, as reflected by the unchanged positive UCM$_{ratio}$. In contrast, variability affecting the center-of-mass increased, as indicated by higher UCM$_{\perp}$, while variability that does not affect the center-of-mass (UCM$_{||}$) remained unchanged.

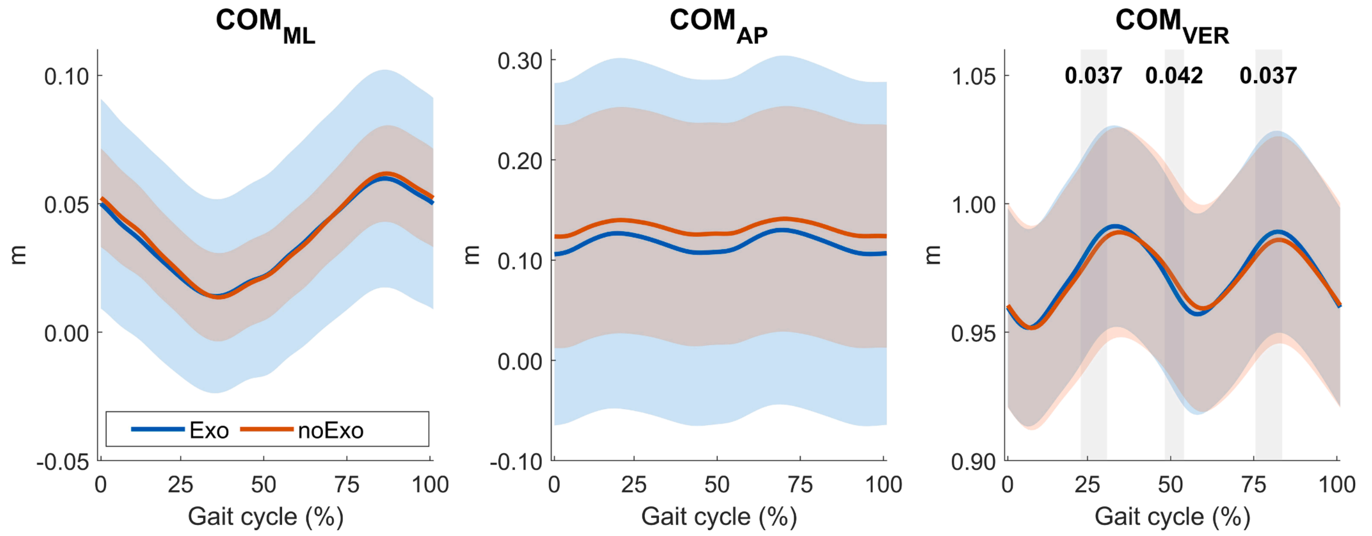

Fig. 3. Center-of-mass position in the mediolateral (COM$_{ML}$), anteroposterior (COM$_{AP}$), and vertical (COM$_{VER}$) directions across the gait cycle for the exoskeleton (Exo, blue) and without exoskeleton (noExo, orange) conditions. Colored shaded areas represent inter-subject variability (± standard deviation). Grey shaded regions indicate significant clusters reflecting differences between Exo and noExo conditions. Corresponding cluster-level p-values are displayed above the shaded regions.

Taken together, these results indicate that the relative balance between task-relevant and task-irrelevant variability was maintained, reflecting a preserved synergy stabilizing the performance variable [20,29]. Accordingly, despite increased variability affecting the center-of-mass, the coordination among joint degrees-of-freedom remained organized to support center-of-mass control.

These findings suggest that exoskeleton assistance was associated with increased variability in the task-relevant dimension without altering the synergy stabilizing center-of-mass. This interpretation aligns with the view that variability is not inherently detrimental [15], but depends on how it is structured with respect to task performance [20,29]. Consistent with previous findings showing that exoskeleton assistance alters joint kinematics and muscle activity, often without substantial changes in overall gait patterns [3,30], the present results indicate that task-level goals (e.g., center-of-mass stability) can be maintained despite changes in joint-level variability.

The preserved synergy may partly relate to the mechanical design of the exoskeleton, which allows three degrees-of-freedom at the ankle and thus imposes fewer kinematic constraints than single degree-of-freedom devices commonly used in previous studies [3,13,30]. Such increased mechanical freedom may facilitate more natural joint coordination and thereby contribute to maintaining task-level control despite altered joint-level variability.

4.2. Small changes in vertical center-of-mass displacement suggest altered push-off mechanics

In line with the final hypothesis, center-of-mass kinematics remained largely unchanged between conditions. The absence of differences in mediolateral and anteroposterior directions suggests that overall whole-body movement was largely preserved under exoskeleton assistance. In contrast, small but significant differences in vertical center-of-mass displacement were observed. Specifically, center-of-mass was slightly higher in the Exo condition during early stance (23–31%) and early swing (75–84%), and lower during mid-stance (48–54%).

These phase-specific changes may be related to alterations in ankle joint function induced by exoskeleton assistance. In particular, the increased vertical center-of-mass displacement during early swing follows the push-off phase and may reflect altered propulsion. Changes observed during stance further suggest that exoskeleton assistance influenced center-of-mass movement during weight acceptance and mid-stance, although the underlying mechanisms cannot be conclusively determined. Given that vertical center-of-mass movement is closely related to propulsion and mechanical energy changes during walking [31,32], these findings are consistent with previous studies showing that ankle exoskeletons modify ankle joint work and push-off dynamics [3,30].

Although joint-angle variability affecting the three-dimensional center-of-mass position increased with the exoskeleton, this did not result in substantial changes in center-of-mass movement. Mediolateral and anteroposterior center-of-mass movement remained unchanged, and only small phase-specific differences were observed in the vertical direction. This suggests that the coordination among joint degrees-of-freedom remained sufficient to maintain three-dimensional center-of-mass movement, in line with the role of multi-joint coordination in whole-body control [33].

This interpretation is consistent with previous findings showing that exoskeleton assistance alters joint kinematics while overall movement patterns remain largely preserved [3,30]. Together, these results support the idea that center-of-mass control can be maintained despite changes in joint-level variability, reflecting the redundant organization of motor control [20,24].

4.3. Limitations

Several limitations should be considered when interpreting the results. First, walking speed was fixed, which may constrain natural adaptations in gait and influence variability structure [34]. Second, the mass and mechanical properties of the exoskeleton may have contributed to the observed effects independently of active assistance [2]. Third, the UCM analysis relied on a linearization around the mean joint configuration, which assumes local linearity and may not fully capture nonlinear coordination patterns. Fourth, although the center-of-mass was selected as the performance variable due to its widely recognized role in the control of whole-body stability during locomotion [18,19,22,35], other task variables are also possible. Fifth, the present analysis compared walking without the exoskeleton with post-familiarization walking with active exoskeleton assistance and did not assess the time course of adaptation. Finally, the study was conducted in healthy young adults during steady treadmill walking, limiting the generalizability to overground walking or clinical populations.

5. Conclusion

In conclusion, walking with active ankle exoskeleton assistance increased joint-level variability that affected center-of-mass position compared with walking without the exoskeleton. However, the overall organization of joint variability and center-of-mass control was preserved, as center-of-mass movement remained largely unchanged. These findings suggest that ankle exoskeleton assistance did not compromise task-level whole-body coordination in healthy adults. From a clinical perspective, this is relevant because assistive devices should not only support propulsion or reduce energetic cost, but also preserve center-of-mass control, which is important for safe and stable walking. Future studies should investigate whether ankle exoskeleton assistance can help restore or improve center-of-mass-related coordination in clinical populations, where balance and center-of-mass control may be impaired.

CRediT authorship contribution statement

Cagla Kettner: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Melina Beyerlein:** Writing – review & editing, Data curation, Conceptualization. **Charlotte Marquardt:** Writing – review & editing, Resources, Data curation. **Miha Dežman:** Writing – review & editing, Resources, Data curation. **Tamim Asfour:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Thorsten Stein:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Ethics approval and consent to participate

All experiments were approved by the Karlsruhe Institute of Technology Ethics Committee. All participants provided written and informed consent to participate.

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Declaration of Competing Interest

All authors read and approved the final manuscript. The authors declare no competing interests.

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