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The effects of soft vs. rigid back-support exoskeletons on trunk dynamic stability and trunk-pelvis coordination in young and old adults during repetitive lifting

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ABSTRACT

While back-support exoskeletons are increasing in popularity as an ergonomic intervention for manual material handling, they may cause alterations to neuromuscular control required for maintaining spinal stability. This study evaluated the effects of soft and rigid passive exoskeletons on trunk local dynamic stability and trunk-pelvis coordination. Thiry-two young (18–30 years) and old (45–60 years) men and women completed repetitive lifting and lowering tasks using two different exoskeletons and in a control condition. Both exoskeletons significantly reduced the short-term maximum Lyapunov exponent (LyE) of the trunk ($p < 0.01$), suggesting improved local dynamic stability. There was also a significant main effect of age ($p = 0.05$): older adults exhibited lower short-term LyE that young adults. Use of the soft exoskeleton significantly increased, while the rigid exoskeleton significantly decreased, long-term LyE, and these changes were more pronounced in the young group compared to the old group. Additionally, exoskeleton use resulted in significant increase ($p < 0.001$) of mean absolute relative phase (MARP) and deviation phase (DP) by ~30–60 %, with greater increases due to the rigid than the soft device. Thus, trunk-pelvic coordination and coordination variability were negatively impacted by exoskeleton use. Potential reasons for these findings may include exoskeleton-induced changes in lifting strategy, reduced peak trunk flexion velocity, and cycle-to-cycle variability of trunk velocity. Furthermore, although the soft and rigid devices caused comparable changes in trunk-extensor muscle activity, they exhibited differential effects on long-term maximum Lyapunov exponents as well as trunk-pelvic coordination, indicating that exoskeleton design features can have complex effects on trunk neuromuscular control.

1. Introduction

Back-support exoskeletons (EXOs) are gaining support as a viable ergonomic intervention for preventing over-exertion injuries in manual material handling (MMH) tasks (de Looze et al., 2016; Nussbaum et al., 2019; Theurel and Desbrosses, 2019). Many recent studies have reported positive benefits such as reduced EMG in the primary trunk extensor muscles with EXO use (Bosch et al., 2016; Luger et al., 2021; Man et al., 2022). However, while reducing physical loading, it is reasonable to expect that external assistance applied through either torque generators or elastic elements of the EXOs may cause redistribution of loads among the low-back musculature, cause different kinematic compensation strategies, and potentially also alter neuromuscular control for maintaining spinal stability.

Given that there is correlation between altered trunk neuromuscular dynamics and low-back disorder risk (Calnan, 2002; Marras et al., 1995; Panjabi, 2003), it is important to understand whether the use of EXOs potentially alters neuromuscular control. Several studies have assessed trunk neuromuscular control by quantifying trunk-pelvis coordination and trunk local dynamic stability – for example, it has been shown that in repetitive lifting, healthy individuals generally show a repeatable and consistent pattern of intersegmental trunk-pelvis coordination. This coordination pattern has been shown to be indicative of neuromuscular control strategies, and sensitive to several factors such as lifting task parameters (Granata and Sanford, 2000), lifting technique (van Dieën et al., 1996), and presence/absence of chronic low-back pain (Esola et al., 1996). Similarly, multiple studies have also shown that trunk dynamic stability during repetitive lifting is sensitive to task and movement characteristics (Graham et al., 2012; Granata and England, 2006), and impaired in those with chronic low back pain (Graham et al.,

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2014; Ross et al., 2015).

Accordingly, a few studies have reported altered trunk dynamic stability and trunk-pelvis coordination when using EXOs. Graham and colleagues (Graham et al., 2011) reported a dramatic decrease (54 %) in the long-term maximum Lyapunov exponent indicating altered neuromuscular control when using the PLAD EXO for repetitive lifting. Following this, Madinei and colleagues (Madinei et al., 2021) evaluated two rigid, passive EXOs (BackX and Laevo V2.5), and reported a relatively smaller increase (of ~8 %) in the short-term maximum Lyapunov exponent when using the Laevo device, and a reduction of ~15 % in trunk-pelvis coordination with both EXOs. While these initial studies indicate some potential altered trunk dynamics with EXO usage, there are still some notable gaps in our understanding of the effects of different EXO designs on alterations in neuromuscular control and trunk dynamic stability. The effects of different design factors such as whether the EXO is soft or rigid (impacting the extent to which they may constrain joint movements), as well as whether the assistance is spring-based or elastic-band based, are currently unknown.

Additionally, most previous studies on the use of EXOs for repetitive lifting have typically recruited only young and healthy subjects. However, complex changes in trunk neuromuscular control have been reported with aging (e.g., Kakar et al., 2022; Sung et al., 2012). Studies have reported compromised local dynamic stability of the trunk among older adults during gait (e.g., Buzzi et al., 2003; Kang and Dingwell, 2009). However, these prior studies showing age-related differences in trunk dynamic stability are limited to gait, and whether their results transfer to lifting is currently unknown. Gender differences have been reported in lifting strategy (Lindbeck and Kjellberg, 2001) and lifting kinematics (Kranz et al., 2021). Furthermore, females adopted different lifting techniques, such as more squatting, compared to males when using a passive rigid EXO (Madinei et al., 2020). Thus, there reason to investigate whether EXOs affect diverse age and gender groups differently, as related to trunk control.

The aim of this study was to quantify the changes in local dynamic stability of trunk and pelvis, and trunk-pelvis coordination, when using soft vs. rigid EXOs to perform repetitive lifting/lowering, among young and old adults. The two different EXOs included a rigid EXO with passive torque generators at the hips and a soft textile-based exosuit with elastic bands running parallel to the trunk extensors. Since users of these devices, especially women, have reported perceived movement restrictions (Alemi et al., 2020; Kozinc et al., 2021), we expected that trunk-pelvis coordination would be negatively affected when using the EXOs, and that the extent to which coordination was affected would be further differentiated by device type and gender. Based on the literature, we expected older adults to demonstrate a more cautious lifting strategy with EXOs, reflected by higher local dynamic stability and lower coordination variability compared to younger adults, when using EXOs versus control.

2. Methods

2.1. Experimental design, setup, and protocols

A convenience sample of 32 healthy adults (8 M and 8 F in young group: 18–30 years; 8 M and 8 F in old group: 45–60 years), with no recent (12 months) history of musculoskeletal injuries/disorders was recruited using flyers, emails, and other standard recruitment materials, from the local community in Clemson, SC. The mean (SD) of age, body mass, and stature of participants were 25.1 (6.1) years, 70.0 (19.8) kg, and 1.70 (0.06) m in the young group, and 51.9 (7.6) years, 77.1 (18.9) kg, and 1.72 (0.09) m in the old group. This research was approved by the Clemson University Institutional Review Board (IRB2021-0843), and written informed consent was obtained from all participants in accordance with the Declaration of Helsinki. The data reported in this study were part of a larger multi-session experiment (Narasimhan Raghuraman et al., 2024).

In this repeated-measures study design, each participant completed a repetitive lifting/lowering task of a 7.3 kg mass, in a control (no-EXO) condition, and while wearing two different EXOs (order of conditions randomized). Participants performed this repetitive task as a free-style lifting and lowering task in the mid-sagittal plane at a horizontal distance of 30 cm, and between waist and mid-shank levels, at a pace of 10 bpm (5 lowers and 5 lifts per minute) continuously for 3 min. The two EXOs in this study differ in design characteristics; the Apex v1 (HeroWear, LLC, Nashville, TN, USA) is a soft EXO weighing 1.6 kg that utilizes elastic bands for assistance, while the Paexo Back v1 (Ottobock SE & Co. KGaA, Duderstadt, Germany) is a rigid EXO weighing 3 kg that utilizes a spring-based mechanism to augment trunk extensor muscles (Fig. 1). Prior to commencing the task, participants were allowed to self-select their preferred assistance level for the Apex (soft) EXO. The Paexo Back (rigid) was set to 'Early-support' mode for all tasks. Participants completed an extensive familiarization session, with ~45 min of exposure to each EXO, while lifting/lowering a variety of different loads in an initial (different) session, prior to collection of experimental data using standardized loads in this study.

2.2. Data collection and analysis

Whole-body segmental kinematics were recorded using a wearable Inertial Measurement Unit system with 17 units (Xsens Awinda, Movella Inc., USA) at 60 Hz, and the data were low pass filtered at 5 Hz using a 4th order bidirectional Butterworth filter. The standard ZXY rotation sequence recommended by ISB was used to analyze kinematic data (Wu et al., 2002). Each 3-min repetitive lifting/lowering task was split into 15 lifting and 15 lowering cycles. From each cycle, triaxial orientations (sagittal, coronal, and transversal planes) and velocities were obtained for the trunk (segment T8) and pelvis segments. We quantified the local dynamic stability of trunk and pelvis segments (Graham et al., 2012), and continuous relative phase of trunk-pelvis coordination (Zehr et al., 2018) using custom MATLAB scripts (The MathWorks™, Natick, MA, USA). Although not analyzed in this study, participants were also instrumented with surface electromyography (EMG) electrodes for monitoring the muscle activities of major muscles in the trunk, abdomen and thighs.

Local dynamic stability was estimated using the maximum finite-time Lyapunov exponent. To avoid bias due to time series length or number of lifting/lowering cycles, a constant sample number (10,800 = 30 cycles × 6 s × 60 Hz) was used (Bruijn et al., 2009). Stability analysis was computed using the Euclidean norm for triaxial trunk and pelvis orientations at each point in time as: $\sqrt{x(t)^2 + y(t)^2 + z(t)^2}$. We created 5-dimensional state-space from the Euclidean norm using the method of delays (T_d) (as described by Granata and England, 2006; Rosenstein et al., 1993). A constant T_d of 36 samples (10 % of 360 samples, i.e., 6 s representing a single cycle of lifting/lowering) was used (Granata and England, 2006). Maximum Lyapunov exponents λ_{max} were calculated from the Euclidean distance between the nearest neighbors in the 5-dimensional state space (Rosenstein et al., 1993). Short ($s\lambda_{max}$) and long ($l\lambda_{max}$) term maximum Lyapunov exponents were computed respectively for 0–0.5 cycles (0–3 s) and 4–10 cycles (24–60 s) (Bruijn et al., 2009). Negative and positive exponents respectively indicate local stability and local instability, with larger exponents indicating a greater sensitivity to local perturbations (Kantz and Schreiber, 2004).

Trunk-pelvis coordination was calculated by the method of Continuous Relative Phase (CRP) (van Emmerik et al., 2016; Zehr et al., 2018). Kinematic variables of trunk (vertebrae T8) and pelvis segment orientations and velocities in the sagittal plane were divided into lowering and lifting cycles. Then each cycle was time-normalized, by interpolating to 101 points translating to 0 – 100 % of the cycle. The interpolated values (angles [θ] and velocities [ω]) were then normalized to be between −1 and +1 (using Eqs. (1) and (2)).

Fig. 1. Paexo Back (rigid) (left) and Herowear Apex (soft) (right) passive back-support exoskeletons.

$$\theta_{i,norm} = 2 \times \frac{\theta_i - \min(\theta)}{\max(\theta) - \min(\theta)} - 1 \tag{1}$$

$$\omega_{i,norm} = \frac{\omega_i}{\max[\max(\omega), \max(-\omega)]} \tag{2}$$

The normalized values were then transformed into phase angles (in rad) using the *arctangent* function. The difference in phase angles of the two segments (trunk and pelvis) was computed to provide trunk-pelvis CRP. Two measures were extracted from this analysis: (1) mean absolute relative phase (MARP), calculated by averaging the relative phase values over the ensemble CRP curve points from all the repeated cycles of lifting; and (2) deviation phase (DP), calculated by obtaining the root mean square of the standard deviations of the ensemble CRP curve at each time instant (Mokhtarinia et al., 2016; Stergiou et al., 2001). Smaller MARP values indicate that the segments are more "in phase" with each other, while smaller DP values indicate lower variability in trunk-pelvic coordination.

2.3. Statistical analyses

Three-way mixed-factor ANOVA models were used to test the effects of EXO condition (EXO, 3 levels, within subjects), Age group (AGE, 2 levels, between subjects), and Gender (GEN, 2 levels, between subjects), separately on short and long term maximum Lyapunov exponents ($s\lambda_{max}$,

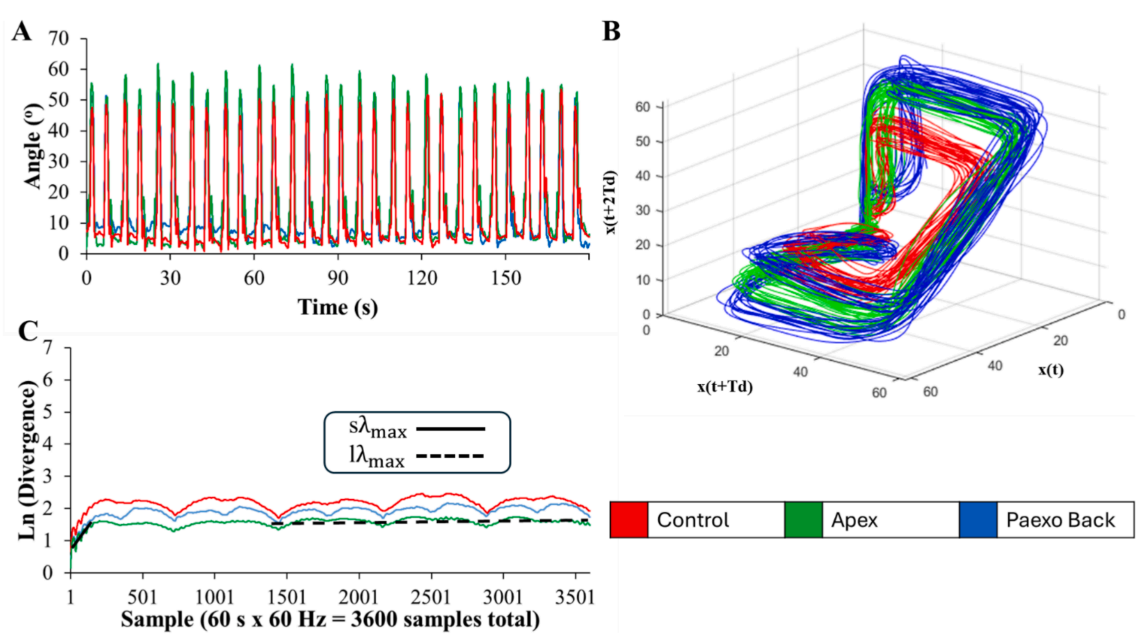

Fig. 2. The process of state space reconstruction and local dynamic stability analyses is described. A: The Euclidean norm of the three angles (coronal, transversal, and sagittal) at each point in time (for 180 s), B: The reconstructed space of the dynamic lifting/lowering motion in 3-D with a time delay of 0.6 s, C: Average logarithmic rate of divergence of all nearest neighbor pairs over a time of 60 s, short-term maximum Lyapunov exponent ($s\lambda_{max}$) and long-term maximum Lyapunov exponent ($l\lambda_{max}$) were calculated using the slope of the curve from 0 to 0.5 cycles and 4 to 10 cycles respectively. The different colored lines indicate different exoskeleton conditions [red: Control, green: Apex (soft), blue: Paexo Back (rigid)].

$l\lambda_{max}$) for trunk and pelvis, and mean absolute relative phase (MARP) and deviation phase (DP) of trunk-pelvis coordination. Significant main effects were followed by post hoc pairwise comparisons (Tukey's HSD) where relevant. All statistical analyses were performed using JMP Pro 14 (SAS, Cary, NC), with statistical significance concluded when $p < 0.05$.

3. Results

3.1. Local dynamic stability

To illustrate the process of state space reconstruction and local dynamic stability analyses, data from an example trial of lifting/lowering (for 3 min) are shown in Fig. 2. Significant main and interaction effects of EXO, AGE, and GEN were found on the short-term and long-term maximum Lyapunov exponents ($s\lambda_{max}$, $l\lambda_{max}$) of trunk and pelvis (Table 1). EXO use significantly reduced the $s\lambda_{max}$ of trunk [$p = 0.005$, by ~5 % for Apex (soft) and ~4 % for Paexo Back (rigid)] and pelvis [$p < 0.0022$, ~12 % for Apex (soft) and ~9 % for Paexo Back (rigid)], as compared to the control condition (Fig. 3, top panel). No significant main effects were observed for EXO on $l\lambda_{max}$ for trunk or pelvis. However, a notable main effect of gender ($p \approx 0.05$), with average $l\lambda_{max}$ values of 0.0006 for males and −0.0004 for females, was observed for the trunk. A significant two-way interaction between EXO and AGE for trunk $l\lambda_{max}$ was also noted ($p = 0.004$). The $l\lambda_{max}$ as a result of using EXOs differed between young groups using Apex (soft) and Paexo Back (rigid) ($l\lambda_{max} = 1.2e{-3}$ and $l\lambda_{max} = -1.9e{-3}$ respectively, Fig. 3, bottom panel).

3.2. Continuous relative phase

An exemplar lift/lower cycle, and computation of CRP measures, are shown in Fig. 4. Analysis of CRP measures (MARP and DP) for lifting and lowering indicated several significant main effects of EXO (Table 1). Use of both EXOs increased MARP and DP significantly (Fig. 5), when compared to the control (no EXO) condition, for both lifting and lowering ($p < 0.001$). During lifting, using Paexo Back (rigid) increased MARP and DP by 59 % and 47 % respectively, and using the Apex (soft) increased MARP and DP by 30 % and 36 % respectively. During lowering, using the Paexo Back (rigid) increased MARP and DP by 63 % and 37 % respectively and using the Apex (soft) increased MARP and DP by 34 % and 20 % respectively. Furthermore, from post-hoc analysis (Tukey's HSD), using the Paexo Back (rigid) further significantly increased MARP in lifting and lowering when compared to the soft Apex (soft) by 22 % and 21 % respectively. There were no significant AGE or GEN interaction effects in CRP measures.

4. Discussion

Both the EXOs (soft and rigid) improved short-term dynamic stability (indicated through a decrease in short-term maximum Lyapunov exponent values). However, the long-term maximum Lyapunov exponents increased when using a soft EXO, and decreased when using a rigid EXO, and these results were more pronounced among younger adults. Trunk-pelvis coordination became more out of phase with EXO usage (more with the rigid than soft EXO), for both lifting and lowering tasks.

4.1. Local dynamic stability

Use of both EXOs reduced $s\lambda_{max}$. Graham et al. (2011) reported a similar $s\lambda_{max}$ of 0.335 in their control condition, but did not find any significant EXO effect of the PLAD (rigid) device on $s\lambda_{max}$. Instead, they reported a significant EXO effect on $l\lambda_{max}$. Another study from Madinei et al. (2021), evaluated two passive rigid EXOs, SuitX BackX and Laevo V2.5 and contrary to our findings, they reported a significant increase in $s\lambda_{max}$ with Laevo (~8 %).

Reduced maximum Lyapunov exponents suggest a decrease in the chaotic behavior or unpredictability of movement. This indicates greater neuromuscular control of trunk stability and/or more controlled movement patterns in the trunk and pelvis regions. Both EXOs provide assistive trunk extension torques, thereby decreasing both trunk muscle activity and compressive spinal loads (Goršič et al., 2021; Kang and Mirka, 2023; Schmalz et al., 2022). Hence, we expected that such decreased muscular effort would lead to reduced muscle stiffness, thereby producing an overall decrease to the neuromuscular control of stability (mechanisms discussed in Cholewicki and McGill, 1996; Crisco and Panjabi, 1991; Gardner-Morse and Stokes, 2001; Graham et al., 2012). However, this was not the case, and using both EXOs improved trunk local dynamic stability. Whether this may be because of the external stiffness of the EXOs devices, increased antagonistic muscle activation, or alterations in lifting styles when using EXOs that may alter both loading and stability, are currently unclear. For example, we have reported in our earlier work that when using the EXOs, participants exhibited a decrease in peak trunk flexion and increase in peak knee flexion, thereby adopting a more "squat" like posture, as compared to the control condition (Narasimhan Raghuraman et al, 2024). However, these changes were small in magnitude (~5–10 %). Since all participants were instructed to perform free-style lifting, there are no controlled data to compare trunk stability across different lifting styles. Hence, whether these changes in peak trunk and knee flexion caused the observed changes in trunk dynamic stability are presently unclear. We explore two additional possible reasons for our findings. First, we had

Table 1
ANOVA outcomes [*p*-values (effect sizes)] of the effects of Exoskeleton (EXO), Gender (GEN), and AGE on local dynamic stability and continuous relative phase. Bold values indicate significant outcomes at $p < 0.05$.

Effect	Outcome					
	EXO	AGE	GEN	EXO × AGE	EXO × GEN	EXO × AGE × GEN
$s\lambda_{max}$ (Trunk)	**0.05 (0.1)**	**0.05 (0.24)**	0.82 (<0.01)	0.45 (0.03)	0.58 (0.02)	0.15 (0.07)
$l\lambda_{max}$ (Trunk)	0.2 (0.06)	0.19 (0.03)	**0.05 (0.06)**	**0.05 (0.1)**	0.98 (<0.01)	0.34 (0.04)
$s\lambda_{max}$ (Pelvis)	**0.002 (0.2)**	0.95 (<0.01)	0.23 (0.09)	0.99 (<0.01)	0.41 (0.03)	0.9 (<0.01)
$l\lambda_{max}$ (Pelvis)	0.13 (0.07)	0.39 (0.01)	0.09 (0.05)	0.16 (0.06)	0.81 (0.01)	0.46 (0.03)
MARP (Lifting)	**0 < 0.0001 (0.4)**	0.23 (0.09)	0.68 (0.01)	0.24 (0.05)	0.79 (<0.01)	0.83 (<0.01)
MARP (Lowering)	**0 < 0.0001 (0.38)**	0.21 (0.07)	0.95 (<0.01)	0.66 (0.01)	0.98 (<0.01)	0.85 (<0.01)
DP (Lifting)	**0 < 0.0001 (0.35)**	0.65 (0.01)	0.54 (0.03)	0.19 (0.05)	0.95 (<0.01)	0.28 (0.04)
DP (Lowering)	**0.002 (0.21)**	0.46 (0.04)	0.73 (<0.01)	0.9 (<0.01)	0.67 (0.01)	0.13 (0.07)

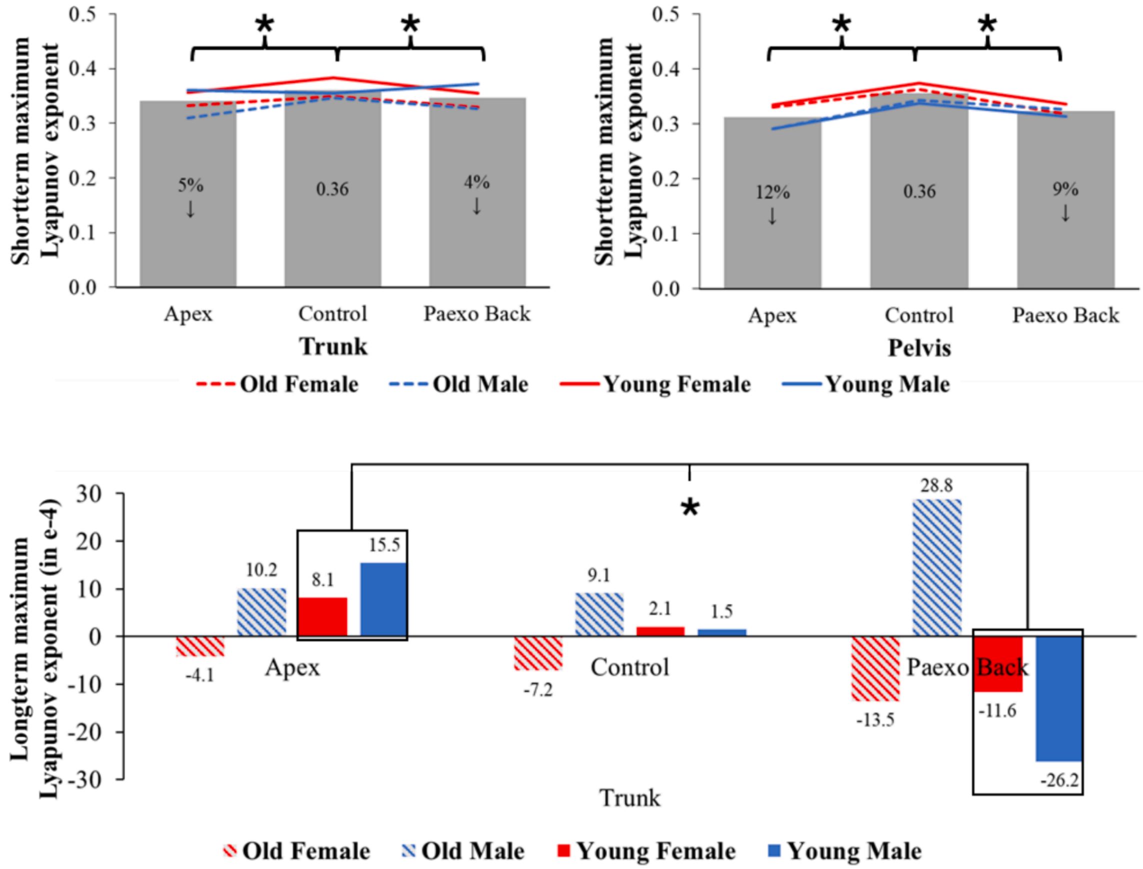

Fig. 3. Top panel: short-term maximum Lyapunov exponent ($s\lambda_{max}$) of trunk and pelvis and Bottom panel: long-term maximum Lyapunov exponent ($l\lambda_{max}$) of trunk for repetitive lifting and lowering in different exoskeleton conditions compared to control (no exoskeleton condition). Gray bars correspond to overall means, overlayed colored lines or colored bars indicate means of different age and gender groups; percentage changes in top panel are with respect to the control condition. Significant effects at $p < 0.05$ are indicated by asterisks.

reported earlier that using both the soft and rigid EXOs led to decreased peak trunk velocity in the sagittal plane (Narasimhan Raghuraman et al., 2024). Granata and England (2006) and Asgari et al. (2015) have reported that trunk movements at higher speeds significantly increased $s\lambda_{max}$. Thus, one potential explanation for the reduced $s\lambda_{max}$ in our study could be that trunk movements slowed down, with the use of EXOs. Alternatively, we also observed significant reductions in the cycle-to-cycle standard deviation of peak trunk velocity when using both EXOs, in lifting and lowering ($p = 0.04$ and $p < 0.01$, respectively, Fig. 6). This suggests that participants may have exhibited more controlled (cautious) movement patterns when using the EXOs, and may also potentially be used to explain the reason for reduction in $s\lambda_{max}$, indicating greater movement stability when using EXOs.

Furthermore, although our main purpose was to examine the effects of EXOs, we also noted that there was a significant effect of age on $s\lambda_{max}$. Older adults, on average, exhibited lower $s\lambda_{max}$, i.e., higher local dynamic stability at the trunk, than younger adults, across all conditions, but no significant interactions between EXO and AGE. While trunk dynamic stability has been studied in young vs. old adults during gait (Kang and Dingwell, 2009) we are not aware of any studies of the effects of age on trunk dynamic stability specific to lifting tasks. Our study shows that older adults exhibit higher local dynamic stability than younger adults during repetitive lifting tasks, suggesting a more cautious lifting pattern among older adults.

In terms of long-term dynamic stability, $l\lambda_{max}$ increased with Apex (soft), as compared to the control condition, and significantly for the younger group. This indicates that the neuromuscular system's ability to respond to local perturbations on longer time scales was deteriorated by wearing the soft EXO. One explanation is that the young group in our study generally preferred stronger levels of assistance from the soft EXO compared to the older group [70 % of the young group vs. 60 % of the old group preferred the "strong" band setting on the Apex (soft) device]. Although not substantial, this may explain the observed EXO × AGE interaction in $l\lambda_{max}$. Alternatively, the age difference in $l\lambda_{max}$ may also reflect age-related differences in compensation strategies to the use of EXOs. Use of Paexo Back (rigid), on the other hand, improved local dynamic stability, as reflected by substantial decrease in $l\lambda_{max}$ in all groups, except for the older males. These findings are in accordance with earlier findings (Graham et al., 2011), where the PLAD (rigid) device substantially decreased $l\lambda_{max}$. Thus, while the soft and rigid EXOs were not different in terms of $s\lambda_{max}$, they were clearly differentiated in terms of their effects on $l\lambda_{max}$. Nevertheless, our findings on $l\lambda_{max}$ are to be interpreted with caution as we studied only 15 repeats of lifting and lowering tasks, which may have affected the precision of the estimates (Bruijn et al., 2009).

4.2. Continuous relative phase

EXO use significantly increased MARP and DP values for both lifting and lowering compared to Control condition indicating a more out of phase trunk-pelvis coordination. Our MARP and DP values in the Control condition were similar to previous reports in the literature on similar tasks (e.g., Zehr et al. (2018)). Madinei et al. (2021) also reported increase in MARP and DP from using two different passive rigid EXOs. However, they reported more modest increases of ~10–13 % in MARP and DP (compared to 30–60 % in our study). We have reported in our earlier work that when using the EXOs, participants tended to adopt a more squat-like-posture, as compared to the control condition

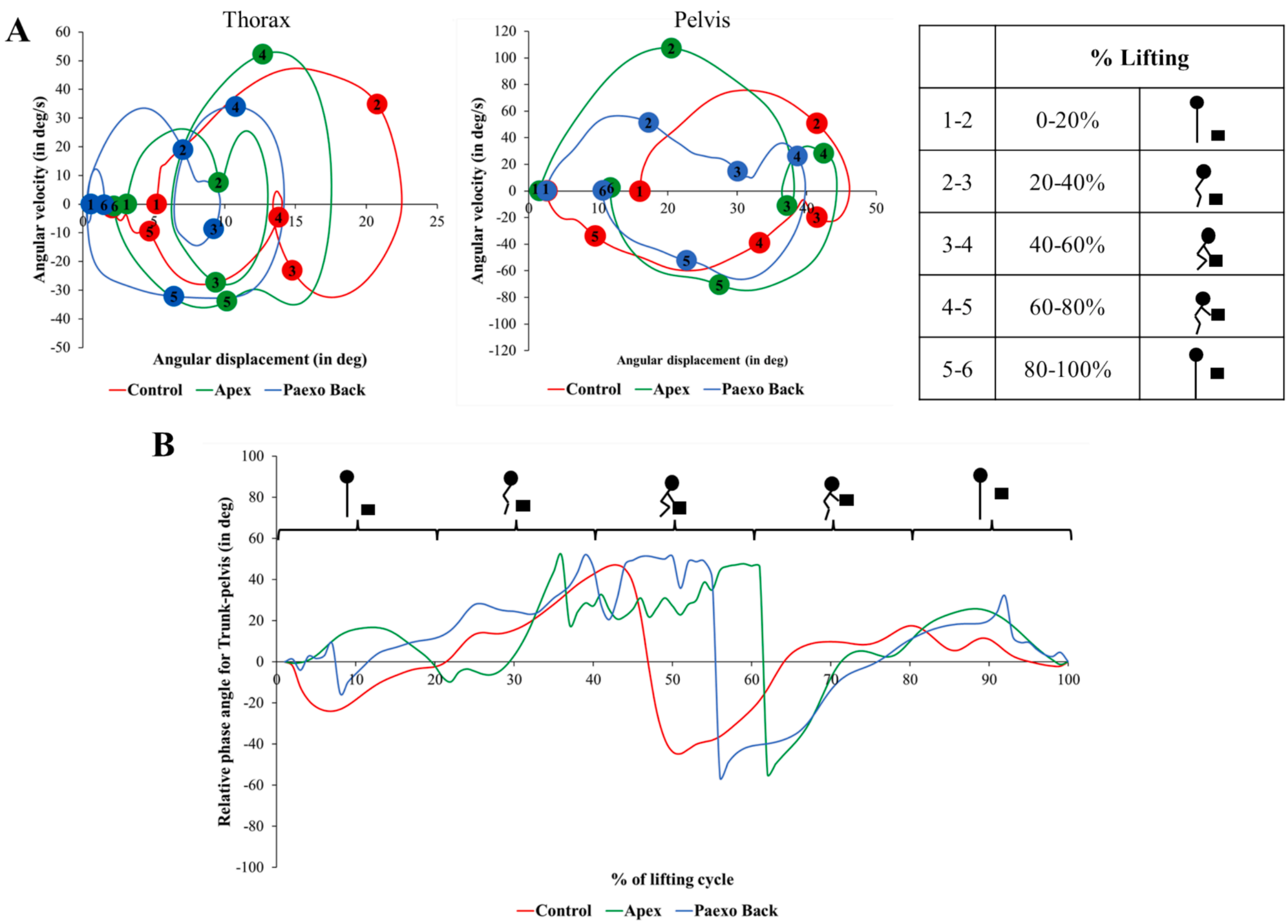

Fig. 4. The process of continuous relative phase analysis for trunk-pelvis coordination during one lifting cycle is described. A: Angular velocity (°/s) vs. Angular displacement (in deg) for Trunk and Pelvis, with each 20 % of the task marked for each exoskeleton condition. B: The relative phase angle of Trunk-Pelvis coordination for the same task cycle. The different colored lines indicate different exoskeleton conditions [red: Control, green: Apex (soft), blue: Paexo Back (rigid)].

(Narasimhan Raghuraman et al., 2024). This may have caused some changes in MARP. Additionally, when looking at Fig. 4, it is evident that the increase in MARP is primarily due to the increase in relative phase of trunk-pelvis coordination that occurs in the middle 40–60 % of the task, which is during the time of peak flexion. This seems largely due to the high positive velocity of the trunk during this time in the EXO conditions, as compared to the control condition. While Fig. 4 only shows data from one person and is to be interpreted with caution, it may be the case that the assistance from the EXO is activated during the time of peak trunk flexion, causing some differences in trunk-pelvic coordination. Whether this increase in MARP has any long-term adverse consequences to the trunk musculature is currently unclear. Previous work (e.g., Pranata et al., 2018) has found that individuals with chronic low back pain tend to have higher MARP than healthy individuals – however, in such studies, increase in MARP was interpreted as a consequence of maladaptation that occurs with persistent pain, and not as a cause of pain.

The increase in DP suggests that trunk-pelvis coordination also became more variable with the use of EXOs. Mokhtarinia and colleagues (Mokhtarinia et al., 2016) reported a significant influence of velocity on trunk-pelvis DP, that slower velocity of flexion–extension movements increased DP by ~21 %. Hence, our findings of increased DP with EXO-use may be attributed, at least partly, to participants moving at a slower pace with EXOs (Fig. 6). Increased DP may also suggest non-stabilized coordination patterns, indicating that participants may be yet to find optimal movement strategies when using EXOs for repetitive lifting/lowering. In our study, participants had an extensive familiarization session prior to experimental task performance (exposed to each EXO for 45–60 min), and performed the same lifting tasks (with differences in only load level), with the same device settings. Hence, the patterns observed in this study were not the initial short-term response to being exposed to a novel assistive device – however, it is unclear whether participants had fully adapted to EXO use by the time of the experiment, or may continue to show adaptations if allowed more exposure time. There is some literature on participants adapting their movement strategies to using EXOs (Gordon and Ferris, 2007; Jacobs et al., 2018; Park et al., 2023; Sawicki and Ferris, 2008), and some preliminary discussions on how long it may take for users to find a new "optimal" movement pattern in the presence of exoskeletal assistance (e.g., Agarwal and Deshpande, 2019; Young and Ferris, 2017). Some of these studies have indicated that stable kinematics (indicative of adaptations) occur in the range of ~45–90 min, while some others, such as those investigating more complex powered whole-body EXOs, have demonstrated that movement strategies do not stabilize even after 3–4 sessions of use. It is, however, difficult to generalize this earlier body of work to passive EXOs, as much of the available literature is largely from powered EXOs and often focused on gait control. Thus, this is an open question in the field, as to *if* there are different optimal movement strategies when using EXOs, how long it may take individuals to find such strategies, and how EXO type, design, assistance levels, and individual factors such as age or gender, may impact motor adaptations when using them.

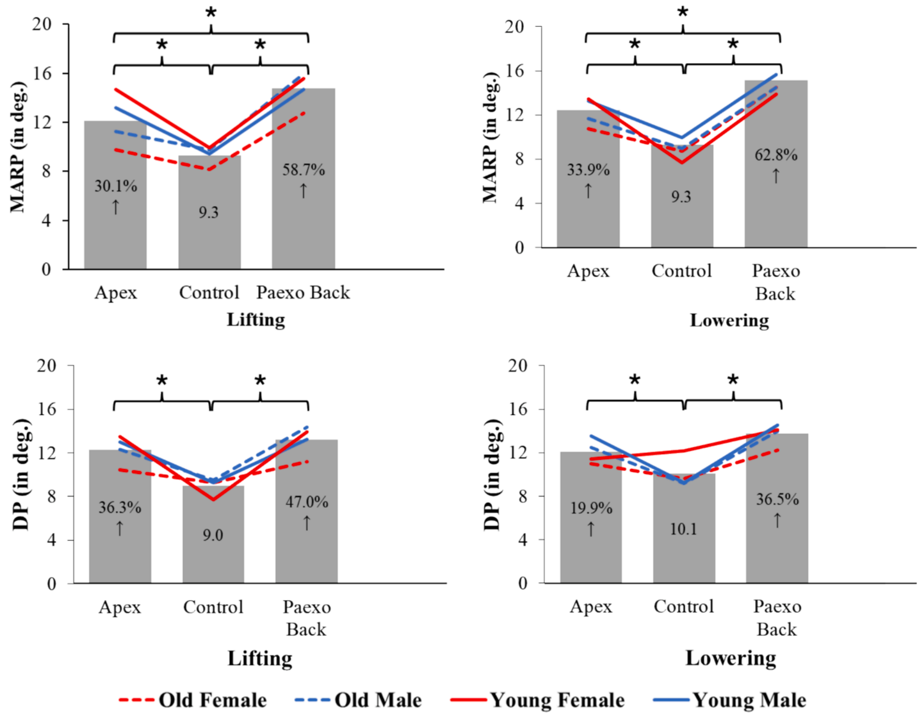

Fig. 5. Top panel: Mean absolute relative phase (MARP) (in deg) for lifting and lowering, bottom panel: Deviation phase (DP) (in deg) for lifting and lowering for the different exoskeleton conditions. Bars indicate overall means, overlayed colored lines indicate different groups, and the percentage change from Control is given within each bar. Significant effects at $p < 0.05$ are indicated by asterisks.

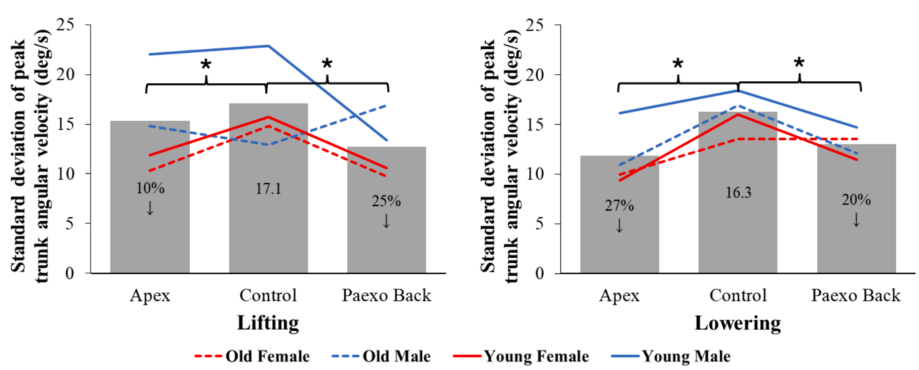

Fig. 6. Cycle-to-cycle standard deviation of peak trunk velocity (in sagittal plane) from 15 cycles of repetitive lifting and lowering, in different exoskeleton conditions. Bars indicate overall means, overlayed colored lines indicate different groups, and the percentage change from Control is given within each bars. Significant effects at $p < 0.05$ are indicated by asterisks.

4.3. Limitations

There were a few limitations in this study. First, our participants were all healthy and not industrial workers, and our results may not be generalizable to workers regularly performing manual material handling tasks, or those with low-back pain. Second, our protocol involving a fixed number of movement cycles (30 lowering and lifting cycles) was designed to avoid muscular fatigue, but may have affected the precision of our estimates of trunk dynamic stability. Finally, to be practically relevant, participants self-selected their preferred assistance level with the Apex (soft) EXO, resulting in potential differences in external device stiffness across individuals.

5. Conclusions

We found clear exoskeleton-design related differences in trunk dynamic stability as well as trunk-pelvic coordination. While both devices improved short-term dynamic stability, their impacts on long-term dynamic stability were significantly different. Back-support exoskeleton use also increased the mean absolute relative phase and deviation phase of trunk-pelvis coordination, suggesting substantial changes in movement strategy. These differences were significantly more pronounced in the rigid than soft exoskeleton. Contrary to our expectations, there were no significant gender differences in any of our outcomes, and older adults exhibited increased local dynamic stability than younger adults. Overall, despite promising short-term benefits, the long-term consequences of routinely using exoskeletons for industrial work performance are not currently well-understood. In this context, our findings contribute to a deeper understanding of how different exoskeleton designs influence neuromuscular control of the trunk during lifting. Future work may need to consider how these measures may adapt over repeated time/exposure to exoskeletons, whether there is a systematic relationship between device assistance level and trunk stability, and include the study of any fatigue-related changes in stability outcomes.

CRediT authorship contribution statement

Rahul Narasimhan Raghuraman: Data collection, Analysis, Manuscript preparation. **Divya Srinivasan:** Conceptualization, Analysis, Manuscript review and editing.

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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