Effects of a Passive Back-Support Exosuit on Postural Control and Cognitive Performance During a Fatigue-Inducing Posture Maintenance Task

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ABSTRACT

Objective: To evaluate the effectiveness of passive-back support exosuit on postural control and cognitive performance during a fatigue-inducing posture maintenance task.

Background: Wearable support systems (exoskeletons/exosuits) reduce physical demands but may also influence postural control and cognitive performance by reducing muscular fatigue.

Method: Eighteen participants visited on two different days to test an exosuit system and performed dual-task cognitive assessments based on human information processing (information acquisition, information integration, and action implementation) while maintaining a 35° trunk flexion posture for 16 minutes. Center-of-pressure (CoP), cognitive performance, and perceived workload were recorded, while erector spinae muscle activity was captured to quantify muscle fatigue.

Results: The exosuit was effective in reducing erector spinae muscle fatigue during the static posture maintenance task (61% less in Δmedian frequency, -9.5 Hz (EXO-Off) vs. -3.8 Hz (EXO-On)). The fatigue-inducing task increased CoP velocity as a function of time (29% greater: 9.3 mm/sec (pre) vs. 12.0 mm/sec (post)), and exosuit use decreased CoP velocity (23% less: 12.1 mm/sec (EXO-Off) vs. 9.4 mm/sec (EXO-On)). The exosuit was also effective at mitigating cognitive degradation, as evidenced by a higher hit-to-signal ratio (8% greater: 81.3 (EXO-Off) vs. 87.9 (EXO-On)) in the information integration task and reducing perceived workload in all stages of human information processing.

Conclusion: Exosuit provided benefits of postural control and information integration processing during a 16-minute static posture maintenance task.

Application: Torso exoskeletons/suits can have positive implications for occupations with concurrent physical and cognitive demands.

Keywords: Exoskeleton; Muscle fatigue; Cognitive performance; Postural control; Information Processing

Précis: The effects of a passive back-support exosuit on postural control and human information processing performance were examined during a fatigue-inducing posture maintenance task. The exosuit was effective in mitigating the degradation of postural control and information integration and reducing the perceived workload at all stages of human information processing.

INTRODUCTION

Wearable support systems (exoskeletons/suits) have emerged as promising ergonomic interventions to reduce low back stress. They can be active (powered) or passive (unpowered), and either rigid or soft in structure (Davis et al., 2020). Passive devices are used in industries due to availability, simple structure, and low-cost (De Looze et al., 2016). Passive systems can provide an additional extension moment during trunk flexion through a supporting device (e.g., spring-damper system) to reduce the force required for the low back muscles (Koopman et al., 2019).

In realistic work settings, many occupations impose both physical and cognitive demands for extended periods. Surgeons operating in an awkward position can have increased muscle fatigue (Luttmann et al., 1996) and perceived pain/discomfort (Dorion & Darveau, 2013; Norasi et al., 2021), which can decrease surgical accuracy (Dorion & Darveau, 2013). A recent study showed a significant decrease in continuous tracking error, tracking speed, and response time in simulated laparoscopy tasks that induced shoulder muscle fatigue (Stephenson et al., 2020).

The present study speculated that enhanced physical ability with wearable support systems could positively affect cognitive function under concurrent physical and cognitive demands. This hypothesis is grounded in the motor unit recruitment process (Bigland-Ritchie et al., 1986; Fallentin et al., 1993; Garland et al., 1994) and attentional investment for postural control (Roerdink et al., 2011a, 2011b). Previous studies have consistently demonstrated that exoskeletons/suits reduced low back muscle activity (Alemi et al., 2019; Madinei et al., 2020; Luger et al., 2021; Tetteh et al., 2022; Kang & Mirka, 2023) and muscle fatigue (Yin et al., 2019; Lamers et al., 2020; Kermavnar et al., 2021). Reduction of back muscle fatigue may prevent the diversion of cognitive resources from supporting and controlling low back musculature, allowing more cognitive resources for cognitive and postural control tasks.

Muscular fatigue can disrupt postural control through various mechanisms, including a negative impact on sensory information accuracy, impaired integration of peripheral afferents within the central nervous system, and reduced effectiveness of motor command recruitment (Ghamkhar & Kahlaee, 2019). Muscular fatigue can result in recruiting more motor units to increase stability in the surrounding fatigued musculature (Bigland-Ritchie et al., 1986) and require more attentional resources to perform tasks (Lorist et al., 2002; Roerdink et al., 2011b; Stephenson et al., 2020; Vuillerme et al., 2002). Pline et al. (2006) reported a noteworthy positive correlation between the fatigue level and duration of trunk extensor muscles, and both sway velocity and time. It is hypothesized that the reduction in trunk extensor muscle activation that results from the use of the exosuit will free-up attentional resources that can then be allocated for better postural control and delay the onset of cognitive impairment associated with muscle fatigue.

Exploring the effects of passive back-support exoskeletons/suits on the human information processing (IP) stage can also provide a deeper insight into the intervention strategy of wearable support systems. Previous studies have generally examined attentional resources in a broad sense without focusing on the stages of human IP (Afzal et al., 2017; Bridger et al., 2018; Bequette et al., 2021; Leibman et al., 2022). Human information processing (IP) can be modeled in four stages: information acquisition; information analysis; decision and action selection; and action implementation (Parasuraman et al., 2000; Kaber et al., 2005), and involves various cognitive mechanics, including sensation, attention, perception, working memory, long-term memory, analysis, decision-making, and motor control (Wickens et al., 2015). Information acquisition and action implementation were considered low-order IP functions, while information analysis and decision-making were considered high-order processing functions. The present study will assess the impact of exosuit intervention on low- and high-order IP stages, similar to the work of Kaber et al. (2005), who investigated the impacts of adaptive automation on IP stages.

The current study hypothesized that a high-order IP task might be more affected by the exosuit compared to low-order IP tasks. Increasing exercise intensity places strain on the metabolic resources of the brain, particularly first impacting the prefrontal cortex responsible for sophisticated cognitive processes (Markowitsch, 1995), followed by other brain regions involved in less complex cognitive processing (Dietrich, 2003). A previous study examined cognition during physical activities, showing that cognitive functions dependent on the prefrontal cortex, such as working memory and attention, were significantly impaired during running compared to sedentary controls (Dietrich & Sparling, 2004). Conversely, cognitive performances requiring little prefrontal activity were not degraded during endurance exercises (Dietrich & Sparling, 2004).

No consensus has been reached on the effects of exoskeletons/suits on cognitive performance. In a study by Bridger and colleagues (2018), an exoskeleton was shown to have no effect on sustained attention performance during a squat position exercise, but reduced time pressure, frustration, conflicting task demands, the need for self-control, and heart rate (Bridger et al., 2018). However, other studies have reported adverse effects of exoskeletons on cognitive performance. Passive back-support exoskeleton used during an asymmetric lifting task decreased peak lateral shear force at L5/S1 but increased cognitive and motor adaptation effort, implying a cognitive-physical trade-off under concurrent demands (Zhu et al., 2021). Leibman et al. (2022)

showed that wearing the exoskeleton resulted in poorer performance on a primary peg-in-hole task, but not a secondary visual attention task. Overall, the exoskeleton effect on cognitive performance remains unclear, requiring further research on the relations between the exoskeleton, physical demand, and cognitive performance. The current study aimed to assess the impact of a passive back-support exosuit on postural control and cognitive performance during a fatigue-inducing posture maintenance task.

METHODS

Participants

Eighteen participants (12 males, 6 females) were recruited from the Ames community (average age 25.3 years (SD=4.8), height 173.6 cm (SD=11.5), and weight 73.0 kg (SD=18.8)). Participants with a history of back or leg; back pain; metal allergies, highly sensitive skin; color blindness; corrected vision less than 20/20; or under 18 years old or over 65 years old were excluded. The institutional review board at Iowa State University, which complied with the American Psychological Association Code of Ethics, approved this study.

Apparatus

The Delsys® Bagnoli-16 electromyography system captured the lumbar erector spinae (ES) muscle activity (Delsys Inc., Boston, MA, USA) (1024 Hz). Two DE-2.1 electromyography sensors were attached to the bilateral ES (4 cm from the vertebral midline at the L3 level). The Bertec® force plate captured the 3-D ground reaction forces and moments (Bertec Inc., Columbus, OH, USA) (1024 Hz). The Trigno® wireless biofeedback system with onboard inertial measurement unit (IMU) monitored trunk flexion angles (relative to neutral standing posture) (Delsys Inc., Boston, MA, USA). One Avanti sensor with an onboard IMU was attached at the C7-T1 vertebral level to monitor trunk flexion angle.

The HeroWear Apex (HeroWear, Nashville, USA) is a low-profile lumbar support exosuit (Figure 1) that consists of textile-based upper-body (e.g., shoulder straps, back part) and lower-body parts (thigh sleeves), secured by elastic bands. Elastic bands naturally stretch as the trunk flexion angle increases to provide a trunk extensor moment. The HeroWear company mentioned that the S1500 elastic bands can provide lumbar extension torque of 13-16 Nm at 30° trunk flexion and 17-24 Nm at 60° trunk flexion, varying by the person based on anthropometry (M. Yandell, personal communication, March 6, 2023).

Experimental setup

Figure 1 depicts the experimental setup of this study. The height of the table was adjusted to facilitate the maintenance of the required 35-degree trunk flexion posture for varied anthropometry of participants. Two Dell® PCs, monitors, and keyboards each hosted cognitive tasks. Participants were asked to stand on the force plate with their feet shoulder-width apart.

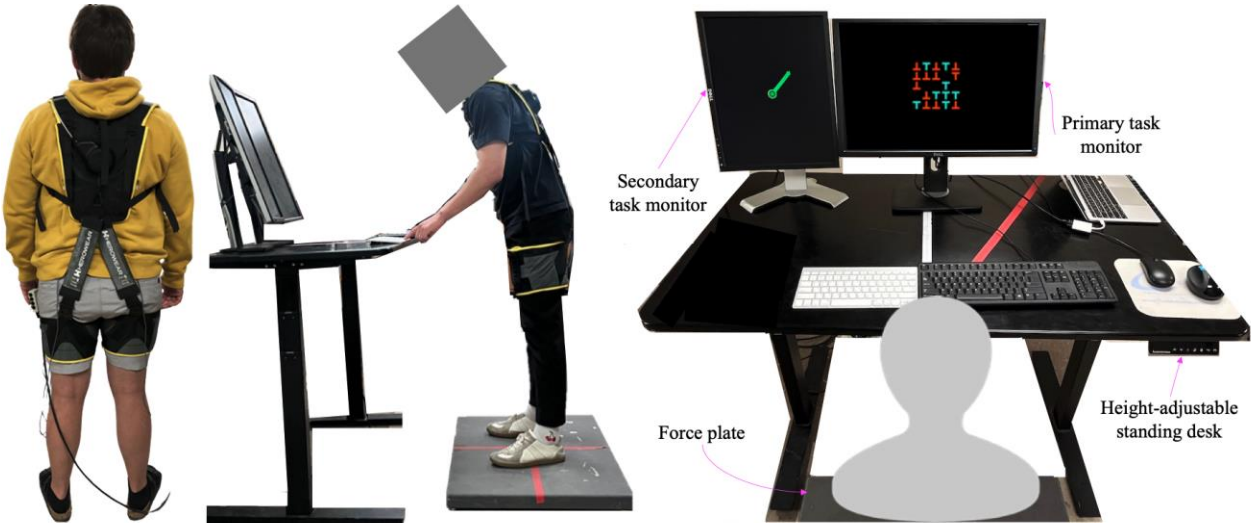

Figure 1. HeroWear exosuit (left), 35° static trunk flexion posture (middle), and experimental setup for cognitive tasks (right).

Tasks

Participants adopted a 35° (± 2°) trunk flexion posture to induce low back muscle fatigue. Participants held this trunk position for four (4-min) time blocks. The 35° trunk flexion angle was chosen as it was found to induce lumbar muscle fatigue while minimizing involvement of lumbar passive tissues (Ning et al., 2012). A 30-sec upright standing break was provided between the four-time blocks.

The dual-task methodology for the cognitive task required participants to allocate attentional resources between multiple tasks (Huang & Mercer, 2001; Stephenson et al., 2020; Wickens, 2008). Three primary tasks were aligned with an IP stage (Table 1): visual search (acquisition), 2-back (integration), and Fitts's pointing task (action). The study integrated two high-order stages (information analysis and decision-making) into the information integration stage since it is difficult to identify tasks that target each high-order stage individually. Cognitive tasks were implemented using the PsyToolkit library (Stoet, 2010, 2017).

Table 1: Mapping between information processing stages and primary cognitive tasks

Information processing stage	**Primary cognitive task**	**References**
Information acquisition	Visual search task	Treisman, 1977; Treisman & Gelade, 1980
Information integration	2-back task	Kirchner, 1958; Kane & Conway, 2007; Jaeggi et al., 2010
Action implementation	Fitts's paradigm pointing task	Fitts, 1954; Fitts & Peterson, 1964; MacKenzie, 2018

The visual search task required participants to focus attention and engage in information acquisition to determine if certain information was displayed (Treisman, 1977). Participants pressed the space bar if they located an upright orange T amid a field of randomly arranged upright blue Ts and upside-down orange Ts. Each scene was displayed for 1.5 sec, and trials were separated by 400 ms.

The 2-back task measured information integration performance (Jaeggi et al., 2010; Kane et al., 2007; Kirchner, 1958). Participants were randomly exposed to one of 15 English letters per trial for 500 ms; 1500 ms between trials. Participants pressed the space bar key when they saw a letter that was the same one they saw two letters ago. As the information integration task, participants had to recognize the letter presented (recognition), recall a 2-back letter from their working memory (recall) and decide whether it was the same or different from the letter presented (decision-making).

Fitts's paradigm-pointing task captured the action implementation stage of the performance (Fitts, 1954; Fitts & Peterson, 1964; MacKenzie, 2018). Participants saw a yellow square appeared in the upper left position (fixed location, 10x10 pixels) and a red square randomly placed in the remaining space. Participants clicked the yellow square and moved the mouse cursor to the red square as fast as possible. The distance between the yellow and red squares and the movement time taken to travel between them with the mouse cursor were recorded. The index of difficulty was calculated as the logarithm base 2 of 2 times the distance between yellow and red squares divided by the width of the square. The index of performance was obtained by dividing the index of difficulty by the movement time (MacKenzie, 2018).

The Mackworth clock task was the secondary task used to capture the amount of residual attentional resources while participants performed their primary tasks (Lichstein et al., 2000; Mackworth, 1948). A green clock hand moved at 3.6 deg/sec in a clockwise direction. A larger jump (10.8 deg) occurred with a probability of 30%. Participants pressed the space bar when detecting the larger jump. They were asked to prioritize the primary task and attend the secondary task as they were able (Kaber et al., 2005).

Experimental Variables

The independent variables for the current study were the activation of the exosuit function (EXO: EXO-On and EXO-Off) and time (TIME: 1 (0-4 min), 2 (4-8 min), 3 (8-12 min), and 4 (12-16 min)). To control for placebo effects of the exosuit use, all participants wore the exosuit during all conditions of the experiment, and the exosuit support mechanism was either engaged (EXO-On) or not engaged (EXO-OFF). Table 2 shows the dependent variables and metrics of this study. The Center-of-Pressure (CoP) variables are likely to be influenced by cognitive tasks, but this applies equally to all eight levels of the independent variables (EXO×TIME), allowing direct comparisons across levels of the independent variable.

Table 2: Dependent Variable Metrics, Units, and Sampling/Query Frequency During Data Collection Procedure

Dependent Variable	Metric	Code	Units	Frequency
Electromyography (EMG): erector spinae muscle activity and fatigue	Average of the normalized EMG	NEMG	%MVC	Each trial
	Change in median frequency of EMG	ΔMDF	Hz	During baseline, each trial
Center-of-Pressure (CoP): postural control while maintaining 35° trunk flexion posture	CoP SD in the anterior-posterior direction	AP SD	mm	Each trial
	CoP SD in the medial-lateral direction	ML SD	mm	Each trial
	95% elliptical area of the deviations of CoP	CoP area	mm2	Each trial
	Travel distance of CoP divided by time	CoP velocity	mm/s	Each trial
Visual search performance	Accuracy, Hit Ratio, FA Ratio	-	percent	Each trial
2-back performance	Accuracy, Hit Ratio FA Ratio	-	percent	Each trial
pointing task performance	Index of Performance	-	bits/sec	Each trial
Mackworth clock task performance	Accuracy, Hit Ratio, FA Ratio	-	percent	Each trial
Perceived workload	NASA TLX (Hart & Staveland, 1988)	TLX	scale 0-20	After each time block
Perceived fatigue	Borg CR10 (Dedering et al., 1999)	Borg	scale 0-10	After each time block

Note. EMG=electromyography; CoP=center-of-pressure; SD=standard deviation; FA=false alarm; CR=correct response; NASA TLX=NASA task load index; CR=Category-Ratio.

Hypotheses

H1: Exosuit use will enhance postural control.

H2: Exosuit use will improve cognitive performance.

H3: Exosuit use will have a greater impact on the high-order information processing task (information integration) than the low-order information processing tasks.

H4: Exosuit use will reduce perceived workload and perceived fatigue.

Procedures

Figure 2 shows the summary of the experimental procedures timeline.

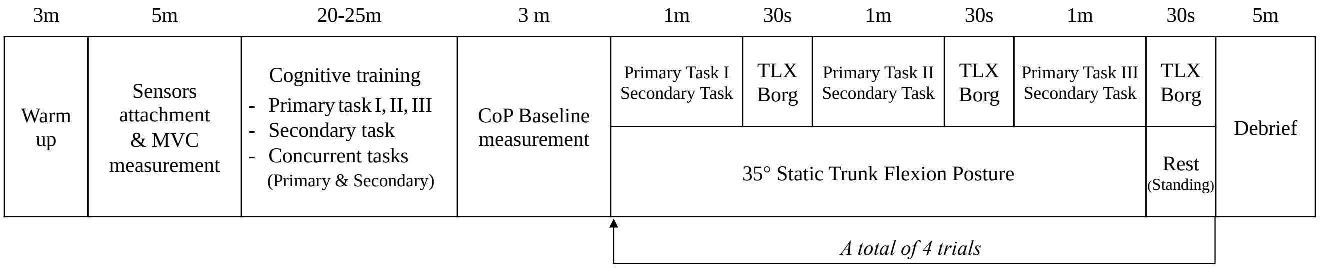

Figure 2. Experimental procedures timeline. MVC=Maximum voluntary contraction; CoP= Center-of-pressure; TLX=NASA Task Load Index; Borg=Borg scale.

Participants participated on two distinct days (one day each for EXO-On and EXO-Off). The order of conditions was counterbalanced among participants. The order of primary tasks was determined with a Latin Square. After informed consent, participants provided age, height, and weight, followed by a brief warm-up session. Two EMG sensors were attached to the skin over the bilateral ES muscles and one IMU sensor was secured to the skin at the C7-T1 level. To capture MVC data from the ES muscles, the participant was immobilized in a Roman chair, bent their torso about 30°, and extended against manual resistance (recorded twice for 3 sec). Participants performed practice maintaining static trunk flexion postures. The baseline for muscle fatigue was then captured in a 35° trunk flexion posture for 30 sec. The cognitive training lasted about 25 min. Participants practiced four cognitive tasks independently and then practiced the primary and secondary tasks concurrently. They were fully briefed/trained on the TLX and Borg scales and proceeded with the main experiment only when they felt confident and were able to respond within the 30-sec time limit.

The main experimental session was a total of 17.5 min, consisting of four-time blocks, lasting four min each, with 30-sec periods of physical and cognitive rest in between. Within each time block, there were three one-minute dual-tasks (differed in primary tasks) and two 30-sec mental rest periods (while maintaining 35° trunk flexion) between each dual-task. During each time block, the participants were asked to hold a 35° trunk flexion posture while the experimenter monitored the trunk flexion angle and provided real-time feedback if the angle was observed to be outside 35° ± 2°. The participants were not asked to focus attention on their postural control because we wanted to quantify the natural changes in CoP variables that resulted from this specific multi-task scenario (cognitive demands and prolonged, posture-maintenance exertion). After each dual-task, participants completed the TLX and Borg surveys and were directed to focus their ratings on the task just completed.

Data analysis

The raw EMG data were converted to the frequency domain and filtered (band pass filter at 10-400 Hz and band stop filter at 60 Hz and their aliases), and the median value of the EMG power spectrum was calculated. The frequency domain data were then converted back to the time domain, demeaned, and full-wave rectified and then EMG amplitudes was averaged for each trial. The MVC data were analyzed using moving average (sliding window: 1/8 sec) to find a maximum value for each side of the ES muscles and used as a denominator to normalize EMG data. Since no significant difference was found between the left-right pairs of the ES muscles, all EMG variables were calculated as the average of left-right pair. The sampled 3-D ground reaction forces (Fx, Fy, Fz) and moments (Mx, My, Mz) were used to calculate instantaneous x-y coordinates of the CoP (Cx, Cy). These calculated time-series CoP data (1024 Hz) were down-sampled to 1/8 (128 Hz) and then smoothed (2nd order low-pass Butterworth filter, cut-off frequency of 12.5 Hz) (Donker et al., 2007). The standard deviation of the CoP for anterior-posterior (AP SD) and medial-lateral (ML SD) directions were then calculated as was the area of the 95% ellipse (CoP area). Finally, the CoP velocity was calculated by summing the total travel distance of the CoP and then dividing it by the duration of the sampling period. The EMG and CoP dependent measures were the average of the three values within each block.

Statistical analysis

All statistical analyses were performed using Minitab® (Minitab Inc, PA, USA). The normality and homoscedasticity assumptions were identified by the Ryan-Joiner test and Levene’s Test. Dependent variables that violated the assumptions were transformed to satisfy the assumptions using the method proposed by Templeton (2011). Multivariate analyses of variances (MANOVAs) were performed on the EMG, CoP, and cognitive measures to control experimental-wise error rates. Analyses of variance (ANOVAs) were employed as follow-up tests if significant main effects and interaction effects were identified in MANOVAs. Finally, the η^2 (eta-squared statistic) was used to establish the effect size of the differences (0.14 – Large effect; 0.06 – Medium effect; 0.01 - Small effect (Cohen, 1988))

RESULTS

Muscular fatigue and postural control

MANOVA results revealed no significant interaction effects between EXO and TIME on the EMG and CoP measures but showed significant main effects of EXO and TIME (Table 3).

Table 3: MANOVA and subsequent ANOVA results for the EMG and CoP measures. Note: Bold values are statistically significant ($p<0.05$). ***Large effect size, **Medium effect Size, * Small effect size.

	Dependent Variables							
	EMG measures			**CoP measures**				
Independent Variables	MANOVA	NEMG	ΔMDF	MANOVA	AP SD	ML SD	CoP area	CoP velocity
EXO	**$p<.001$** **$F=140.99$**	**$p<.001$** **$F=131.42$** **$\eta^2=.136**$**	**$p<.001$** **$F=78.87$** **$\eta^2=.216***$**	**$p<.001$** **$F=13.41$**	**$p=.037$** **$F=4.47$** **$\eta^2=.014*$**	**$p=.034$** **$F=4.59$** **$\eta^2=.017*$**	**$p=.003$** **$F=8.97$** **$\eta^2=.025*$**	**$p<.001$** **$F=48.75$** **$\eta^2=.073**$**
TIME	**$p=.001$** **$F=3.78$**	$p=.302$ $F=1.23$ $\eta^2=.004$	**$p=.001$** **$F=5.50$** **$\eta^2=.045*$**	**$p<.001$** **$F=3.84$**	**$p<.001$** **$F=7.43$** **$\eta^2=.069**$**	**$p=.004$** **$F=4.71$** **$\eta^2=.051*$**	**$p<.001$** **$F=10.32$** **$\eta^2=.087**$**	**$p<.001$** **$F=11.96$** **$\eta^2=.053*$**
EXO×TIME	$p=.977$ $F=0.20$	-	-	$p=.138$ $F=1.46$	-	-	-	-

ANOVAs on EMG measures revealed a significant EXO effect in NEMG and ΔMDF (Table 3). The NEMG value in EXO-On conditions (8.3 %MVC) was less than EXO-Off conditions (10.7 %MVC), while the result of ΔMDF was significantly greater in EXO-On conditions (-3.8 Hz) compared to the EXO-Off conditions (-9.5 Hz) (Figure 3). These results indicate that the exosuit was effective at reducing muscle activity/fatigue in the low back musculature regardless of level of TIME. A significant TIME effect for ΔMDF indicate increased muscle fatigue as a function of time.

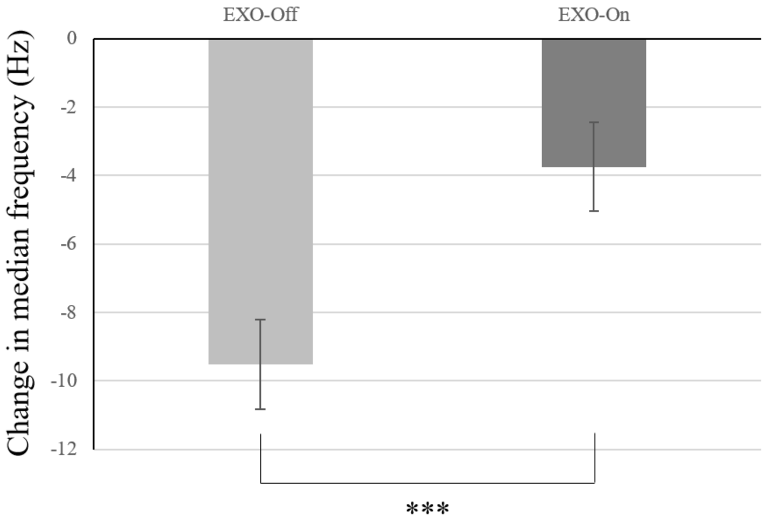

Figure 3. Main effect of EXO for change in median frequency (ΔMDF) of the lumbar erector spinae. Error bars show the standard error of the sample mean (Δ-3.8 Hz; 72.4 Hz to 68.6 Hz) compared to the EXO-Off conditions (Δ-9.5 Hz; 77.6 Hz to 68.1 Hz). *** indicates p≤0.001.

ANOVAs on CoP measures showed a significant EXO effect in CoP velocity and CoP variability (Table 3). The CoP velocity and CoP area in EXO-Off conditions were significantly greater than in EXO-On conditions (23% CoP velocity; 28% CoP area; 15% AP SD; 9% ML SD) (Figure 4). Significant TIME effects, regardless of exosuit use, indicated the impaired postural control induced by low back muscle fatigue.

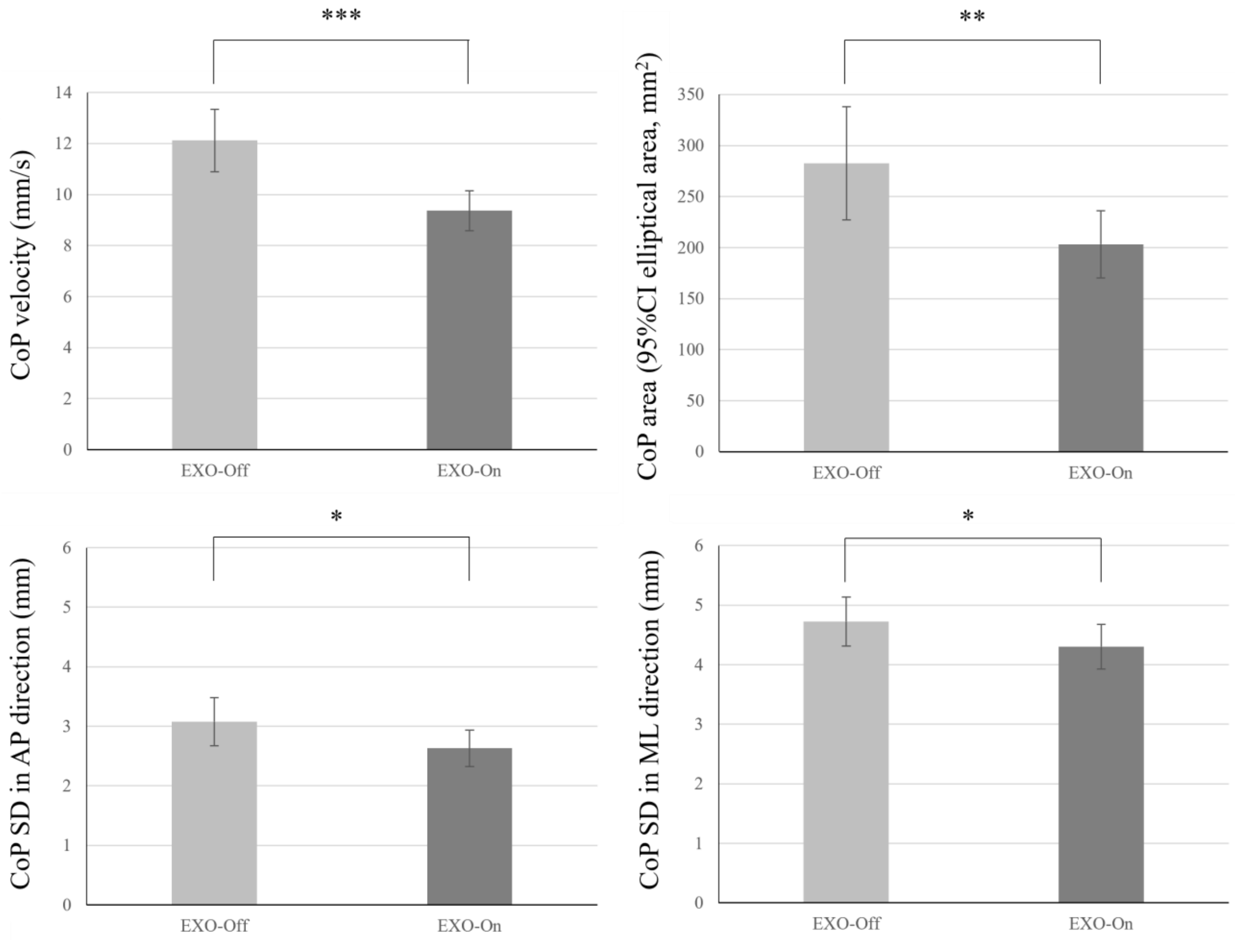

Figure 4. Main effect of EXO for velocity and variability of the center-of-pressure (CoP). Error bars show the standard error of the sample mean. * indicates $p<0.05$; ** indicates $p\leq0.01$; *** indicates $p\leq0.001$.

Perceived workload and fatigue

MANOVAs with subjective measures showed significant main effects of EXO and TIME, but no significant interaction effects (Table 4). ANOVAs on subjective measures in all cognitive tasks revealed a significant main effect of EXO on mental demand, physical demand, performance, effort, frustration, total TLX, and perceived fatigue. Temporal demand was also significantly affected by EXO in the 2-back and Fitts's pointing. Participants reported lower perceived workload and fatigue in the EXO-On compared to the EXO-Off (Figure 5). A significant TIME effect indicated increased perceived workload and fatigue as a function of time.

Table 4: MANOVA and subsequent ANOVA results for the subjective measures in each cognitive task. Note 1: Bold values are statistically significant ($p<0.05$). Note 2: FA=False alarm, Fatig.=Fatigue, Ment.=Mental demand, Phys.=Physical demand, Temp.=Temporal demand, Perf.=Performance, Frust.=Frustration, TLX=NASA TLX. ***Large effect size, **Medium effect Size, * Small effect size.

Independent Variables	Dependent Variables: Subjective Measures								
Visual Search	MANOVA	Ment.	Phys.	Temp.	Perf.	Effort	Frust.	TLX total	Fatigue (Borg)
EXO	**$p<.001$** **$F=9.22$**	**$p<.001$** **$F=15.24$** **$\eta^2=.043$****	**$p<.001$** **$F=60.18$** **$\eta^2=.192$*****	$p=.111$ $F=2.58$ $\eta^2=.009$	**$p=.004$** **$F=8.54$** **$\eta^2=.041$***	**$p<.001$** **$F=40.66$** **$\eta^2=.150$*****	**$p<.001$** **$F=23.96$** **$\eta^2=.088$****	**$p<.001$** **$F=38.22$** **$\eta^2=.129$****	**$p<.001$** **$F=56.50$** **$\eta^2=.181$*****
TIME	**$p<.001$** **$F=2.36$**	$p=.249$ $F=1.39$ $\eta^2=.010$	**$p<.001$** **$F=10.07$** **$\eta^2=.090$****	$p=.616$ $F=0.60$ $\eta^2=.006$	$p=.442$ $F=0.90$ $\eta^2=.014$	**$p=.001$** **$F=5.48$** **$\eta^2=.055$***	**$p=.003$** **$F=5.03$** **$\eta^2=.051$***	**$p=.001$** **$F=5.56$** **$\eta^2=.053$***	**$p<.001$** **$F=15.62$** **$\eta^2=.156$*****
EXO ×TIME	$p=.664$ $F=0.86$	-	-	-	-	-	-	-	-
2-Back	MANOVA	Ment.	Phys.	Temp.	Perf.	Effort	Frust.	TLX total	Fatigue (Borg)
EXO	**$p<.001$** **$F=8.91$**	**$p<.001$** **$F=19.84$** **$\eta^2=.067$****	**$p<.001$** **$F=54.04$** **$\eta^2=.173$*****	**$p=.011$** **$F=6.74$** **$\eta^2=.019$***	**$p<.001$** **$F=17.49$** **$\eta^2=.074$****	**$p<.001$** **$F=27.57$** **$\eta^2=.089$****	**$p<.001$** **$F=13.16$** **$\eta^2=.041$***	**$p<.001$** **$F=35.56$** **$\eta^2=.109$****	**$p<.001$** **$F=47.23$** **$\eta^2=.120$****
TIME	**$p<.001$** **$F=2.66$**	$p=.754$ $F=0.40$ $\eta^2=.004$	**$p=.001$** **$F=5.98$** **$\eta^2=.059$***	$p=.131$ $F=1.92$ $\eta^2=.018$	$p=.501$ $F=0.79$ $\eta^2=.010$	**$p=.002$** **$F=5.22$** **$\eta^2=.055$***	**$p=.011$** **$F=3.91$** **$\eta^2=.038$***	**$p=.006$** **$F=4.33$** **$\eta^2=.042$***	**$p<.001$** **$F=19.15$** **$\eta^2=.151$*****
EXO ×TIME	$p=.955$ $F=0.56$	-	-	-	-	-	-	-	-
Fitts's Pointing	MANOVA	Ment.	Phys.	Temp.	Perf.	Effort	Frust.	TLX total	Fatigue (Borg)
EXO	**$p<.001$** **$F=8.56$**	**$p<.001$** **$F=14.17$** **$\eta^2=.045$***	**$p<.001$** **$F=64.98$** **$\eta^2=.235$*****	**$p=.006$** **$F=7.84$** **$\eta^2=.030$***	**$p=.001$** **$F=11.76$** **$\eta^2=.051$***	**$p<.001$** **$F=37.70$** **$\eta^2=.143$*****	**$p<.001$** **$F=27.38$** **$\eta^2=.093$****	**$p<.001$** **$F=32.77$** **$\eta^2=.129$****	**$p<.001$** **$F=39.73$** **$\eta^2=.135$****
TIME	**$p<.001$** **$F=2.97$**	**$p=.002$** **$F=5.07$** **$\eta^2=.049$***	**$p=.003$** **$F=4.85$** **$\eta^2=.053$***	$p=.369$ $F=1.06$ $\eta^2=.013$	$p=.936$ $F=0.14$ $\eta^2=.002$	**$p=.014$** **$F=3.67$** **$\eta^2=.041$***	**$p=.004$** **$F=4.78$** **$\eta^2=.049$***	**$p=.029$** **$F=3.11$** **$\eta^2=.037$***	**$p<.001$** **$F=13.27$** **$\eta^2=.135$****
EXO ×TIME	$p=.273$ $F=1.16$	-	-	-	-	-	-	-	-

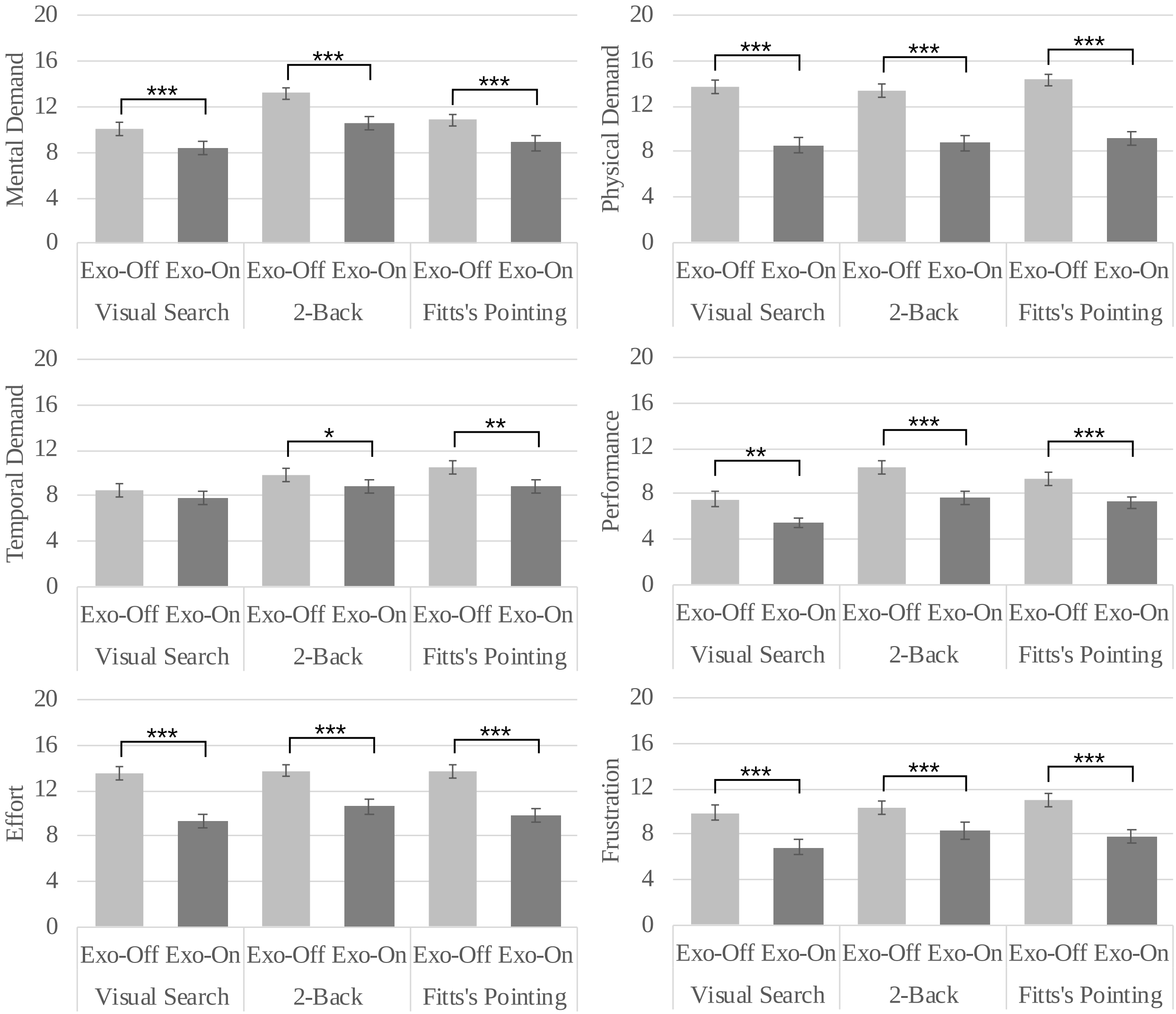

Figure 5. Main effect of EXO for NASA Task Load Index dimensions. Error bars show the standard error. * indicates $p<0.05$; ** indicates $p\leq0.01$; *** indicates $p\leq0.001$.

Cognitive performance

MANOVAs revealed no significant effects for visual search, a significant main effect of EXO in the 2-back, and the main effect of EXO and TIME in Fitts's pointing. No significant interaction effects between EXO and TIME were found (Table 5).

During 2-back, the primary task's accuracy (92.7%) and hit ratio (87.9%) in EXO-On were significantly higher than those of EXO-Off (accuracy: 89.0%, hit ratio: 81.3%), respectively (Figure 6). The primary task's false alarm ratio of EXO-On (4.9%) showed a trend towards being lower than that of EXO-Off (6.7%) (*p*=0.052). The secondary task's false alarm ratio of EXO-On (2.8%) was significantly lower than that of EXO-Off (3.8%).

In Fitts’s pointing, the secondary task’s hit ratio in EXO-On (42.0%) was significantly higher than EXO-Off (36.3%). The secondary task’s false alarm ratio in EXO-Off (2.0%) was significantly lower than that of EXO-On (3.1%). A significant TIME effect for the false alarm rate indicated that the false alarm rate decreased over time.

Table 5: MANOVA and subsequent ANOVA results for the cognitive task measures. Note 1: Bold values are statistically significant (*p*<0.05). Note 2: FA=False alarm. ***Large effect size, **Medium effect Size, * Small effect size.

Independent Variables	Dependent Variables: Objective Measures						
Visual Search	MANOVA	Primary task			Secondary task		
		Accuracy	Hit Ratio	FA Ratio	Accuracy	Hit Ratio	FA Ratio
EXO	p=.700 F=.64	-	-	-	-	-	-
TIME	p=.340 F=1.11	-	-	-	-	-	-
EXO ×TIME	p=.948 F=.520	-	-	-	-	-	-
2-Back	MANOVA	Primary task			Secondary task		
		Accuracy	Hit Ratio	FA Ratio	Accuracy	Hit Ratio	FA Ratio
EXO	**p=.020** **F=2.64**	**p=.001** **F=10.58** **η^2=.051***	**p=.012** **F=6.50** **η^2=.042***	p=.052 F=3.85 η^2=.013	p=.337 F=0.93 η^2=.002	p=.528 F=0.40 η^2=.000	**p=.042** **F=4.22** **η^2=.027***
TIME	p=.903 F=0.59	-	-	-	-	-	-
EXO ×TIME	p=.472 F=0.99	-	-	-	-	-	-
Fitts’s Pointing	MANOVA	Primary task			Secondary task		
		Index of Performance			Accuracy	Hit Ratio	FA Ratio
EXO	**p=.003** **F=4.28**	p=.160 F=2.00 η^2=.002			p=.571 F=0.32 η^2=.002	**p=.016** **F=6.03** **η^2=.024***	**p=.004** **F=8.48** **η^2=.061****
TIME	**p=.033** **F=1.90**	p=.068 F=2.44 η^2=.007			p=.160 F=1.75 η^2=.026	p=.267 F=1.33 η^2=.014	**p=.045** **F=2.77** **η^2=.048***
EXO ×TIME	p=.296 F=1.18	-			-	-	-

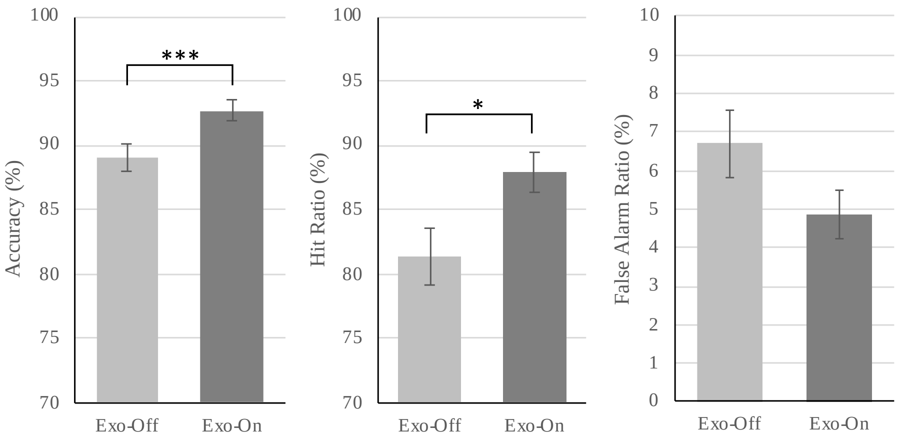

Figure 6. Main effect of EXO for cognitive performance during the 2-back task. Error bars show the standard error. * indicates p<0.05; ** indicates p<0.01; *** indicates p≤0.001.

DISCUSSION

The results revealed that the exosuit use significantly reduced ES muscle activity at 35° static trunk flexion posture (22% reduction), similar to previous studies (Tetteh et al., 2022; Kang & Mirka, 2023). The reduced muscle activity eventually decreased the fatigue development in the ES, consistent with the results of Lamers et al. (2020). Collectively, this study confirmed that the passive back-support exosuit could effectively reduce low back muscle activity/fatigue during static, no-load trunk posture maintenance tasks.

The results of this study supported *H1* in that the exosuit use generated lower levels of CoP velocity and a smaller CoP 95% confidence ellipse. The effect size of these responses was modest (medium and small for CoP velocity and CoP 95% confidence ellipse, respectively) and thus our interpretation of these results is that the exosuit provided a modest increase in postural control, indicating that the reduction in lumbar extensor fatigue through the use of the exosuit may free-up attentional resources that can be applied in the form of greater postural control. An alternative interpretation is that the exosuit reduced the low back fatigue level and under conditions of greater fatigue there might have been more body sway to reduce fatigue-related discomfort. A deeper investigation of the results, however, indicated that the magnitude of the reduction in variability in the CoP measures between the exosuit and no exosuit conditions is similar in both the anterior-posterior and medial-lateral directions and the typical response to physical fatigue is side-to-side (i.e. medial-lateral) swaying (Cham & Redfern, 2001), and our results do provide support for this alternative interpretation. Our interpretation of these results is that the exosuit can provide beneficial effects on postural control for occupations that might require prolonged trunk posture maintenance. For example, if the exosuit system is used by surgeons who maintain static trunk flexion postures for extended period of time, the reduction in muscle fatigue from use of the exosuit can benefit postural control, which could decrease surgical mishaps and improve patient safety. It is interesting to note that these postural control effects were most prominent during the last 12-16 min. Although no significant interaction effect was found, the CoP velocity and variability in EXO-Off conditions gradually increased over time, whereas those values in EXO-On conditions maintained similar levels. These indicate that the effectiveness of exosuit on postural control might be increased as back muscle fatigue accumulates, but further study employing longer periods of time is needed to draw conclusions regarding the impact of time on the effectiveness of the exosuit in postural control.

Some studies on lower body exoskeletons have drawn similar conclusions. Jeffrey et al. (2008) found that the use of the prototype exoskeletal device reduced the limits of stability in the medial-lateral direction and decreased body sway in the anterior-posterior and medial-lateral directions while carrying military loads of 20, 40, and 55 kg. In other task modes, such as squatting (Ramadurai et al., 2022) and walking (Parik-Americano et al., 2022), the lower extremity exoskeleton also improves postural control. However, only one study explored the effect of a passive back-support exoskeleton on postural balance, but this study used upright standing, which implies that the exoskeleton cannot provide an additional supporting force (Park et al., 2021). They showed that the exoskeleton use reduced CoP displacement and CoP area in a unipedal stance, denoting the more stable postural balance. The current study demonstrated that the exosuit could provide postural stability by mitigating the fatigue effects over time at static trunk flexion posture, where the exosuit can provide sufficient trunk extension moment.

H2 regarding the positive effect of the exosuit on cognitive performance was partially supported. Specifically, exosuit use increased the accuracy and hit ratio for the 2-back and decreased the perceived mental workload in all stages of human IP evaluated, together with the reduction in lumbar extensor muscle activation/fatigue. The effect sizes were small to medium for these differences. Considering the results of previous studies that muscular fatigue can require more attentional resources to perform cognitive tasks (e.g., Lorist et al., 2002; Vuillerme et al., 2002; Stephenson et al., 2020), the available attentional resources freed-up due to the reduced muscle fatigue might be used for cognitive processing based on the limited attentional capacity (Kahneman, 1973; Wickens, 1992). Notably, the exosuit effectiveness in information integration processing was most prominent during the initial 0-4 min, when the highest level of muscle fatigue was observed in the EXO-Off (-7.3 Hz for ΔMDF). This indicates that attentional resources utilized for cognitive processing may depend on the rate of developed muscle fatigue per unit time, rather than on accumulated muscle fatigue. Overall, this study suggests that reducing lumbar extensor muscle fatigue through exosuit use can free-up attentional resources to be used for cognitive function, particularly during the early stages of fatigue development.

The significant main effects of EXO on primary cognitive performance were only observed in the high-order IP task (2-back), related to working memory and decision-making, supporting the *H3*. These effects were not observed in the low-order IP tasks (visual search and

Fitts's pointing). During 2-back, the EXO-On showed higher accuracy (4.1%) and hit ratio (8.1%) than the EXO-Off. Conversely, the primary task performances of low-order IP tasks did not show significant differences in the EXO-On compared to the EXO-Off. These suggest that high-order IP tasks are more sensitive to muscle fatigue, and by reducing muscle fatigue through a wearable support system, errors related to high-order IP can be mitigated. Additionally, in the action implementation task (Fitts's pointing), the EXO-On enabled participants to conserve attentional resources and execute actions more effectively for the secondary task. This was evident in the increased action execution, regardless of their correctness. When the exosuit was activated, participants had more successful hits on the signal but also a higher rate of false alarms.

Exosuit use reduced the perceived workload and fatigue across all stages of human IP (*H4*). Compared to the EXO-Off, the EXO-On reduced the subjective NASA TLX measures of mental demand, physical demand, performance, effort, and frustration (15 of 20 effect sizes categorized as large), despite the cognitive tasks being equally challenging in both conditions. These results indicate that mental resources become more strained as muscle fatigue and postural sway increase. Consequently, this study reveals the significant utility of the exosuit in cognitive measures compared to previous studies (Afzal et al., 2017; Bequette et al., 2020; Bridger et al., 2018; Leibman et al., 2022; Zhu et al., 2021).

This study has limitations that should be considered when generalizing its results. First, there might be variations in dual-task proficiency among participants. This individual difference in each cohort could bias the experimental results, affecting the observed effects of exosuit use. Second, the physical task utilized involved maintaining a fixed trunk flexion posture without variability, which may not fully represent real-world occupational situations. Future research could simulate real-world work task profiles, such as product assembly and surgery, to further clarify the effects of muscle fatigue on work performance and the effectiveness of wearable systems. Third, the frequent collection of TLX scores, conducted three times per trial (once after each task), might have influenced the results. This frequent collection might have, in itself, impacted the perceived cognitive workload. Although participants were pre-trained in the survey response process, the potential for added cognitive load should be acknowledged. Fourth, the CoP results, especially for the medial-lateral direction, may have been inflated due to participants intentionally moved their bodies to reduce fatigue-related discomfort. Lastly, the duration of trunk posture maintenance task (16 min) adopted in this study is shorter than actual work time. Future study considering longer periods of time is needed to draw conclusions on the impact of time/muscle fatigue on the effectiveness of an exosuit in postural control and cognitive performance.

CONCLUSION

This study demonstrated that a passive back-support exosuit could prevent postural sway and improve cognitive performance. The exosuit provided enhanced stability in body movements and mitigated cognitive degradation associated with information integration during a fatigue-inducing posture maintenance task. Additionally, the exosuit effectively reduced the perceived workload across all IP stages. These findings suggest that the ability of the exosuit to reduce muscular fatigue enables the allocation of attentional resources to postural control and cognitive performance. As a result, this type of wearable system shows promise in providing both physical and cognitive benefits for occupations involving concurrent physical and cognitive demands, such as surgeons, assemblers, and welders.

KEY POINTS

- This study explored whether attentional resources freed-up by passive back-support exosuit use during a fatigue-inducing posture maintenance task contribute to better postural control and cognitive performance.
- For cognitive performance, this study employed three dual-task cognitive assessments depending on human information processing stages (information acquisition, information integration, and action implementation).
- The exosuit was effective in enhancing postural control and information integration performance and reducing perceived workload in all stages of human information processing.
- Some occupations with concurrent physical and cognitive workloads might be beneficial from the use of exoskeleton intervention.

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