

Occupational arm-support and back-support exoskeletons elicit changes in reactive balance after slip-like and trip-like perturbations on a treadmill

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1 **Abstract**

2 The purpose of this study was to investigate the effects of arm- and back-support exoskeletons  
3 on reactive balance after slip-like and trip-like perturbations on a treadmill. Twenty-eight  
4 participants used two arm-support exoskeletons and two back-support exoskeletons with support  
5 (i.e., assistive joint torque) activated or deactivated. In each exoskeleton condition, as well in as a  
6 control without any exoskeleton, participants were exposed to 12 treadmill perturbations during  
7 upright standing. The exoskeletons did not significantly increase the probability of a failed  
8 recovery after the perturbations compared to wearing no exoskeleton, but did elicit effects on  
9 kinematic variables that suggested balance recovery was more challenging. Moreover, reactive  
10 balance differed when wearing back-support and arm-support exoskeletons, and when wearing  
11 an activated exoskeleton compared to a deactivated exoskeleton. Together, our results suggest  
12 these exoskeletons may increase the risk of slip- and trip-induced falls. The potential  
13 mechanisms of this increased risk are discussed and include the added mass and/or motion  
14 restrictions associated with wearing these exoskeletons. Our results do not support the assistive  
15 hip/back extension moment provided by back-support exoskeletons adversely affecting fall risk.

16  
17 Keywords: *exoskeletons, balance recovery, falls*

18

19 **Introduction**

20 Occupational exoskeletons (EXOs) are wearable devices designed to reduce physical demands  
21 and contribute to reducing musculoskeletal disorder (MSD) risk. Numerous studies have  
22 demonstrated that EXOs can indeed reduce physical demands (de Vries and de Looze, 2019;  
23 Kermavnar et al., 2021; McFarland and Fischer, 2019; Moeller et al., 2022). During repetitive  
24 lifting, for example, using a back-support EXO resulted in a reduction in spinal loading of up to  
25 35% (Madinei and Nussbaum, 2023) and a reduction in back muscle activity of up to 20%  
26 (Madinei et al., 2020). During a static posture with forward trunk bending, using a back-support  
27 EXO resulted in a reduction in spinal loading of up to 12% (Ulrey and Fathallah, 2013) and a  
28 reduction in back muscle activity of up to 57% (Bosch et al., 2016; Koopman et al., 2019).  
29 Similarly, during a simulated manual material handling task involving overhead work, using an  
30 arm-support EXO reduced deltoid and activity by up to 54% (Bar et al., 2021; Maurice et al.,  
31 2020; Pinho and Forner-Cordero, 2022), and mitigated fatigue-related MSD risks and  
32 performance reductions during work tasks involving arm elevation such as overhead drilling (De  
33 Bock et al., 2023; Gillette and Stephenson, 2019). Overall, the current literature supports the  
34 potential of EXOs as an ergonomic control to reduce MSD risks during selected work tasks,  
35 although field evidence of risk reduction remains very limited.

36

37 Several studies have also reported potentially undesirable outcomes from EXOs that may  
38 actually increase injury risk (Kranenborg et al., 2023). For example, arm-support EXOs can  
39 increase heart rate and postural strain (Theurel et al., 2018), while back-support EXOs can  
40 increase discomfort during movement (Kim et al., 2020), restrict lower limb movement during  
41 walking (Kermavnar et al., 2021), and decrease performance and increase perceived difficulty

42 during walking and climbing steps (Baltrusch et al., 2018). Recent evidence also suggests that  
43 EXOs may exacerbate the risk of trip- and slip-induced falls. This is particularly important given  
44 that slips, trips, and falls are already the most costly cause of nonfatal workplace injuries in the  
45 United States (Liberty Mutual Insurance, 2022). For example, back-support EXOs decrease step  
46 length, increase step width, and increase step variability during gait (Park et al., 2022a). They  
47 also decrease hip and knee motion and angular velocity when stepping after a loss of balance  
48 (Park et al., 2022b). Furthermore, a leg-support EXO that provides chair-like support can  
49 adversely affect reactive balance after slip-like and trip-like perturbations on a treadmill (Dooley  
50 et al., 2023). A better understanding of the effects of EXOs on reactive balance could help  
51 increase awareness of these concerns and contribute to the development of strategies to mitigate  
52 fall risk during their use.

53

54 To this end, the purpose of this study was to investigate the effects of passive arm- and back-  
55 support EXOs on reactive balance after slip-like and trip-like perturbations on a treadmill. Both  
56 arm-support and back-support EXOs were investigated based on their potential to differentially  
57 affect reactive balance and fall risk. Our first hypothesis was that arm- and back-support EXOs  
58 would adversely affect reactive balance compared to not wearing an EXO. This hypothesis was  
59 based on the idea that the added mass and/or resistance to some joint movements caused by  
60 EXOs could adversely affect torso control and reactive stepping, which are critically important  
61 when reacting to a slip or trip to avert a fall. Our second hypothesis was that reactive balance  
62 would differ between back-support EXOs and arm-support EXOs. This hypothesis was based on  
63 the assumption that back-support EXOs affect hip function more substantially than arm-support  
64 EXOs, and that hip function is critical during slip and trip recovery. Our third hypothesis was

65 that reactive balance would differ between wearing an activated EXO (i.e., with the torque-  
66 generating mechanism turned on) and a deactivated EXO (i.e., with the torque-generating  
67 mechanism turned off). This hypothesis was based on the presumption that the assistive moment  
68 provided by an activated EXO has greater potential to interfere with the user's desired  
69 movements than a deactivated EXO.

70

## 71 **Methods**

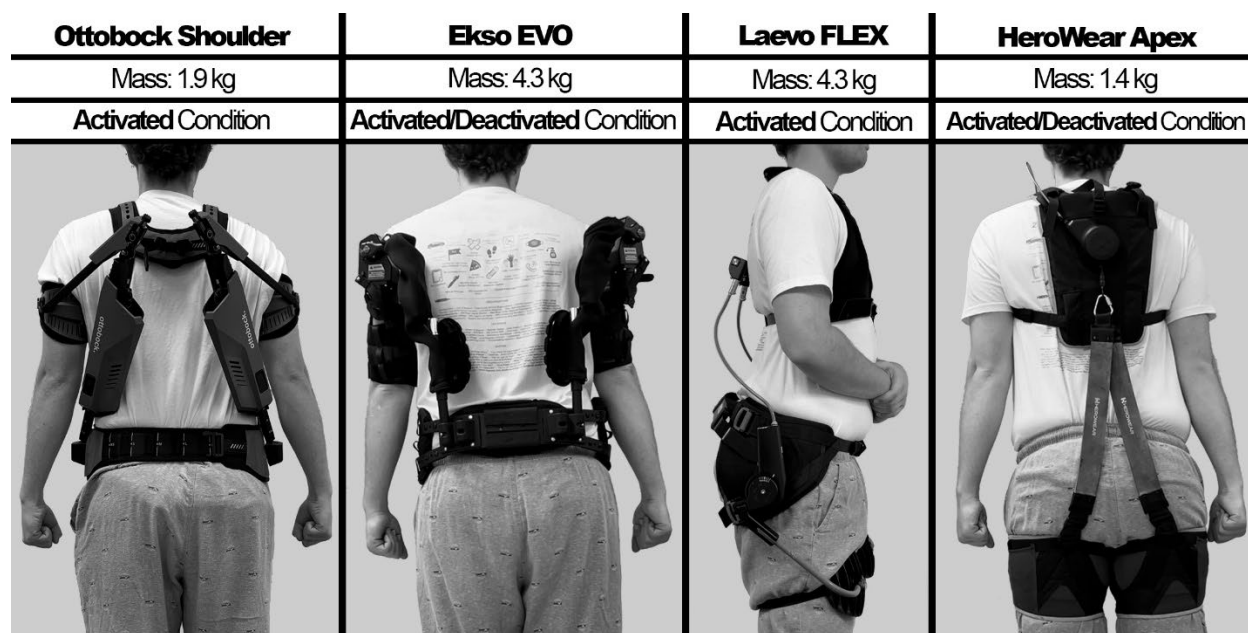
72 A sex-balanced convenience sample of twenty-eight young adults (14 females: age mean  $\pm$   
73 standard deviation =  $21.9 \pm 2.3$  years; stature =  $1.61 \pm 0.09$  m; mass =  $66.2 \pm 10.2$  kg; 14 males:  
74 age =  $22.1 \pm 1.8$  years; height =  $1.71 \pm 0.08$  m; mass =  $81.3 \pm 14.8$  kg;) was recruited from the  
75 university population and completed the study. Inclusion criteria were no injuries in the past  
76 year, body mass index less than  $30 \text{ kg/m}^2$ , age 18-30 years old, and not being pregnant. All  
77 participants provided written consent prior to participation, and the study was approved by the  
78 Virginia Tech Institutional Review Board.

79

80 Two arm-support EXOs and two back-support EXOs were tested (Figure 1). The two arm-  
81 support EXOs were the Ottobock Shoulder (Ottobock Biomics, Duderstadt, Germany) and Ekso  
82 EVO (Ekso Bionics, San Rafael, CA, USA), and the two back-support EXOs were the Laevo  
83 FLEX (Laevo Exoskeletons, Delft, Netherlands) and HeroWear Apex (HeroWear, Nashville,  
84 TN, USA). These EXOs were selected based upon their availability to the researchers and to  
85 represent some of the variability in existing design approaches. The Ottobock Shoulder (arm-  
86 support) and Laevo FLEX (back-support) were not designed to be worn while deactivated, while  
87 the Ekso EVO (arm-support) and HeroWear Apex (back-support) can be worn while activated or

88 deactivated. This resulted in six experimental conditions, and a seventh was added that involved  
 89 no EXO. The presentation order of the experimental conditions for each participant was  
 90 prescribed using 5x5 Latin Squares with activated and deactivated states for the Ekso EVO (arm-  
 91 support) and HeroWear Apex (back-support) completed consecutively in a counterbalanced  
 92 order for efficiency.

93



94

95 Figure 1. Photographs of a user wearing each exoskeleton. The seven experimental conditions  
 96 include Ottobock Shoulder activated, Ekso EVO activated and deactivated, Laevo FLEX  
 97 activated, HeroWear Apex activated and deactivated, and no exoskeleton (not shown).

98

99 Within each experimental condition, participants were exposed to six slip-like and six trip-like  
 100 perturbations over a range of speeds and in a random order. Slip-like perturbations resulted in a  
 101 backward loss of balance, similar to a slip at heel strike while walking over-ground, and typically  
 102 require backward stepping and torso/hip height control for recovery. Trip-like perturbations  
 103 resulted in a forward loss of balance, similar to a trip while walking over-ground, and typically  
 104 require forward stepping and torso/hip height control for recovery. These perturbations were

105 identical to those used elsewhere (e.g., Dusane and Bhatt, 2020; Nevisipour and Honeycutt,  
106 2020). The use of treadmill perturbations, rather than multiple slips and trips while walking,  
107 provided greater experimental control over perturbation initial conditions and severity.

108

109 At the start of each perturbation, the participant stood relaxed on the treadmill (Fully  
110 Instrumented Treadmill, Bertec, Columbus, OH). Participants were instructed to simply react  
111 naturally and try to maintain their balance. They were then asked to count backwards by three,  
112 out loud, from a random two-digit number provided by the investigator to provide a distraction  
113 from the impending perturbation. After a short delay of random duration, the treadmill belt was  
114 accelerated either forward or backward without warning to a constant speed, requiring the  
115 participant to execute a stepping response and to establish a stable gait. Forward treadmill belt  
116 movement induced a slip-like backward loss of balance, and the three perturbations speeds were  
117 0.6, 1.0, and 1.4 m/s. Backward treadmill belt movement induced a trip-like forward loss of  
118 balance, and the three perturbation speeds were 1.0, 1.5, and 2.0 m/s. Each set of 12  
119 perturbations included two repetitions at each of these six speeds. After the participant  
120 established a stable gait or was fully supported by an overhead safety harness because balance  
121 could not be recovered, the treadmill belt was slowed to a halt. The length of the overhead  
122 harness was chosen such that the participant's knee was 10 cm above the belt when attempting to  
123 kneel. No practice trials were provided prior to the start of testing, and a 5-minute rest break was  
124 provided between conditions.

125

126 Whole-body kinematics were sampled at 100 Hz using reflective markers (10 Vero cameras,  
127 Vicon, Centennial, CO, USA – see Supplementary File for locations). Ground reaction forces

128 were sampled at 1000 Hz using force plates integrated into the treadmill. Forces applied to the  
129 harness for support were sampled at 1000 Hz using a load cell (ATO Inc., Diamond Bar, CA,  
130 USA). Kinematic and ground reaction force data were low-pass filtered (4<sup>th</sup> order zero-phase-  
131 shift Butterworth) at 10 and 300 Hz, respectively (Schreven et al., 2015). Harness force data was  
132 not filtered.

133  
134 Several dependent variables were used to assess reactive balance. Perturbation outcome was  
135 either a successful or failed recovery, with the latter determined when the force applied to the  
136 harness exceeded 30% of body weight (Yang and Pai, 2011). Dependent variables of torso and  
137 stepping kinematics were adopted from prior studies on over-ground and treadmill slips and trips  
138 (Allin et al., 2018; Brodie et al., 2018; Dooley et al., 2023; Dusane et al., 2019; Owings et al.,  
139 2001); these variables were included to provide insight on the mechanisms by which EXOs may  
140 affect reactive balance. Specific variables were determined at touchdown of the initial recovery  
141 step (i.e., when vertical ground reaction force exceeded 5 N), and as projections onto the sagittal  
142 plane. For slip-like perturbations, the kinematic variables included step length, step speed, pelvis  
143 height (expressed as % of pelvis height while standing), and stepping toe position (the distance  
144 between the stepping toe and pelvis at touchdown of the initial recovery step). Pelvis position  
145 was estimated to be the midpoint between the greater trochanter markers because the EXOs did  
146 not allow consistent pelvis marker locations. For trip-like perturbations, the kinematic variables  
147 included step length, step speed, torso angle relative to standing, and torso angular velocity.

148  
149 All three study hypotheses were addressed by statistical analyses of the percentage of failed  
150 recoveries and of the kinematic variables. The former was analyzed using logistic (Lasso)

151 regression models with AICc validation to explore the effects of condition, speed, sex, and their  
152 two- and three-way interactions. Kinematic variables were investigated using mixed-factor  
153 analyses of variance (ANOVAs) to explore the effects of the same factors. The presentation  
154 order of the seven conditions, trial number, and sex were included as blocking variables, and  
155 body mass and stature were included as covariates. Our first hypothesis was also addressed using  
156 the kinematic variables and Tukey's HSD for *a priori* pair-wise comparisons between the no-  
157 EXO condition and all others. Our second and third hypotheses were also addressed using the  
158 kinematic variables and contrasts between the relevant conditions. Kinematic data were excluded  
159 from the ANOVA model if > 30% of body weight was applied to the harness prior to initial step  
160 touchdown (61 of 2,352 trials) or if the data were corrupted at any point during the trial (7 of  
161 2,352 trials). All statistical analyses were performed using JMP Pro 16.0 (SAS Institute Inc.,  
162 Cary, NC, USA) with statistical significance concluded when  $p \leq 0.05$ .

163

## 164 **Results**

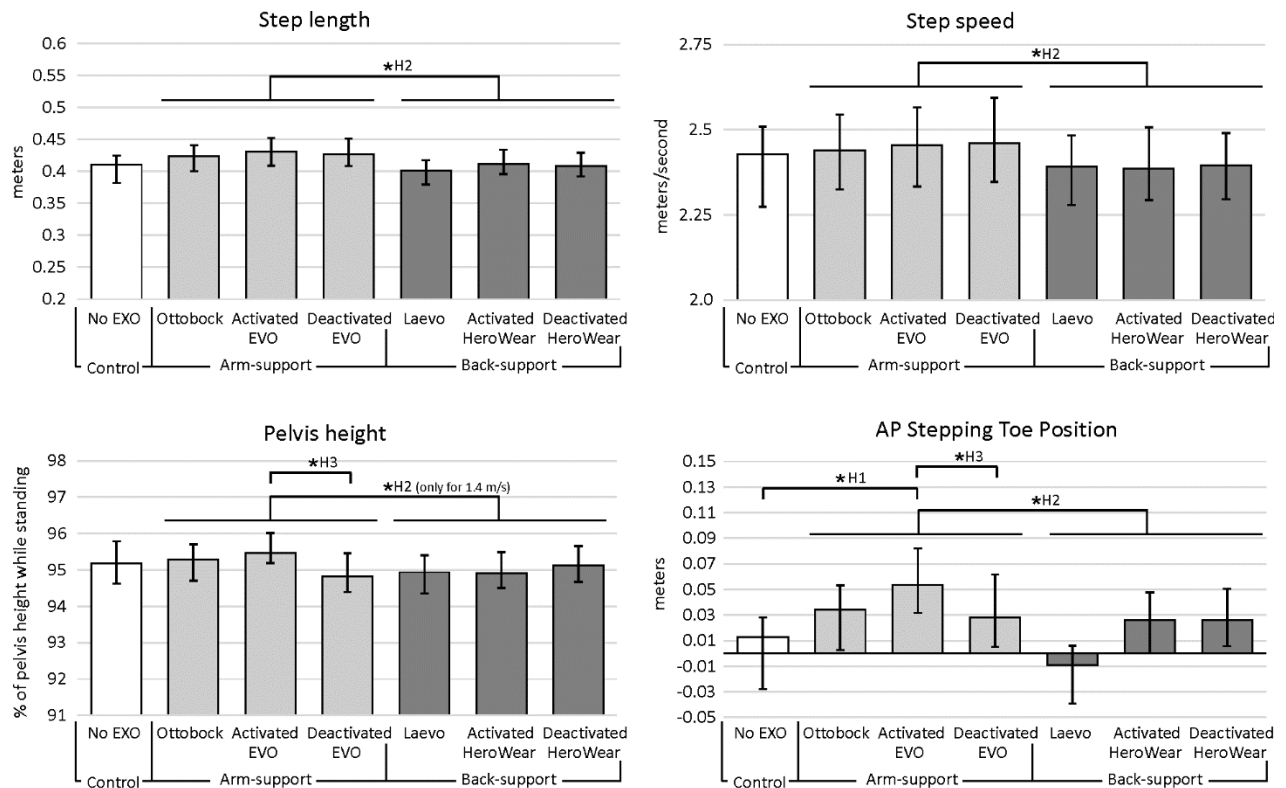
165 After slip-like perturbations, the percentage of failed recoveries was 20.1% across all speeds,  
166 ranging from 2.8% at the slowest speed of 0.6 m/s to 44.4% at the fastest speed of 1.4 m/s. The  
167 percentage of failed recoveries exhibited no interactive effects involving condition ( $p > 0.777$ )  
168 and no main effect of condition ( $p = 0.195$ ). Regarding our first hypothesis, stepping toe position  
169 was 4.1 cm more posterior with the activated Ekso EVO (arm-support;  $p = 0.007$ ) than the no-  
170 EXO condition. Regarding our second hypothesis, step length was 2.0 cm shorter ( $p < 0.001$ ),  
171 step speed was 6.1 cm/s slower ( $p = 0.017$ ), and the stepping toe position was 2.4 cm more  
172 posterior ( $p < 0.001$ ) with the arm-support EXOs than with the back-support EXOs. Pelvis  
173 height did exhibit a condition x speed interaction ( $p = 0.041$ ) because it was 0.66% of its

174 standing height higher with the arm-support EXOs than with the back-support EXOs at the 1.4  
 175 m/s perturbation speed. These differences did not exist at perturbation speeds of 0.6 m/s and 1.0  
 176 m/s. Regarding our third hypothesis, pelvis height was 0.64% of its standing height ( $p = 0.003$ )  
 177 higher, and stepping toe position was 2.6 cm more posterior, with the Ekso EVO (arm-support)  
 178 activated than with it deactivated ( $p = 0.022$ ). No other effects that addressed our hypotheses  
 179 were statistically significant (Table 1; Figure 2; and effect sizes are reported in the  
 180 Supplementary Material).

181 Table 1. Statistical results of kinematic variables of reactive balance after slips. Entries are  $p$   
 182 values from ANOVAs with \* indicating  $p \leq 0.05$ .

	Mass	Height	Order	Trial	Sex	Condition	Speed	Sex* Condition	Speed* Condition	Sex* Speed	Sex*Speed* Condition
<b>Step Length</b>	0.013*	0.085	<0.001*	0.255	0.132	0.005*	<0.001*	0.898	0.393	<0.001*	0.269
<b>Step Speed</b>	0.019*	0.680	<0.001*	0.438	0.157	0.417	<0.001*	0.750	0.122	<0.001*	0.441
<b>Pelvis Height</b>	0.806	0.066	<0.001*	0.556	0.239	0.033*	<0.001*	0.434	0.041*	<0.001*	0.977
<b>AP Pelvis-to-Toe Distance</b>	0.015*	0.531	<0.001*	0.632	0.080	<0.001*	<0.001*	0.227	0.823	<0.001*	0.218

183



184

185 Figure 2. Kinematic variables of reactive balance after slip-like perturbations in each of the  
 186 seven experimental conditions. Columns indicate least squares means and error bars indicate  
 187 95% confidence intervals. Note that none of the y-axes start at zero; rather, scales were used to  
 188 represent typical variable ranges. A positive (negative) stepping toe position indicated the toe  
 189 was posterior (anterior) to the pelvis. Horizontal lines labeled with \* indicate conditions, or  
 190 groups of conditions, that significantly differed ( $p \leq 0.05$ ). H1-H3 labels indicate which  
 191 hypothesis corresponds to each statistically significant result.

192

193 After trip-like perturbations, the percentage of failed recoveries was 12.5% across all speeds,  
 194 ranging from 0.5% at the slowest speed of 1.0 m/s to 31.5% at the fastest speed of 2.0 m/s. The  
 195 percentage of failed recoveries exhibited no interactions involving condition ( $p > 0.469$ ) and no  
 196 main effect of condition ( $p = 0.140$ ). Regarding our first hypothesis, there were several

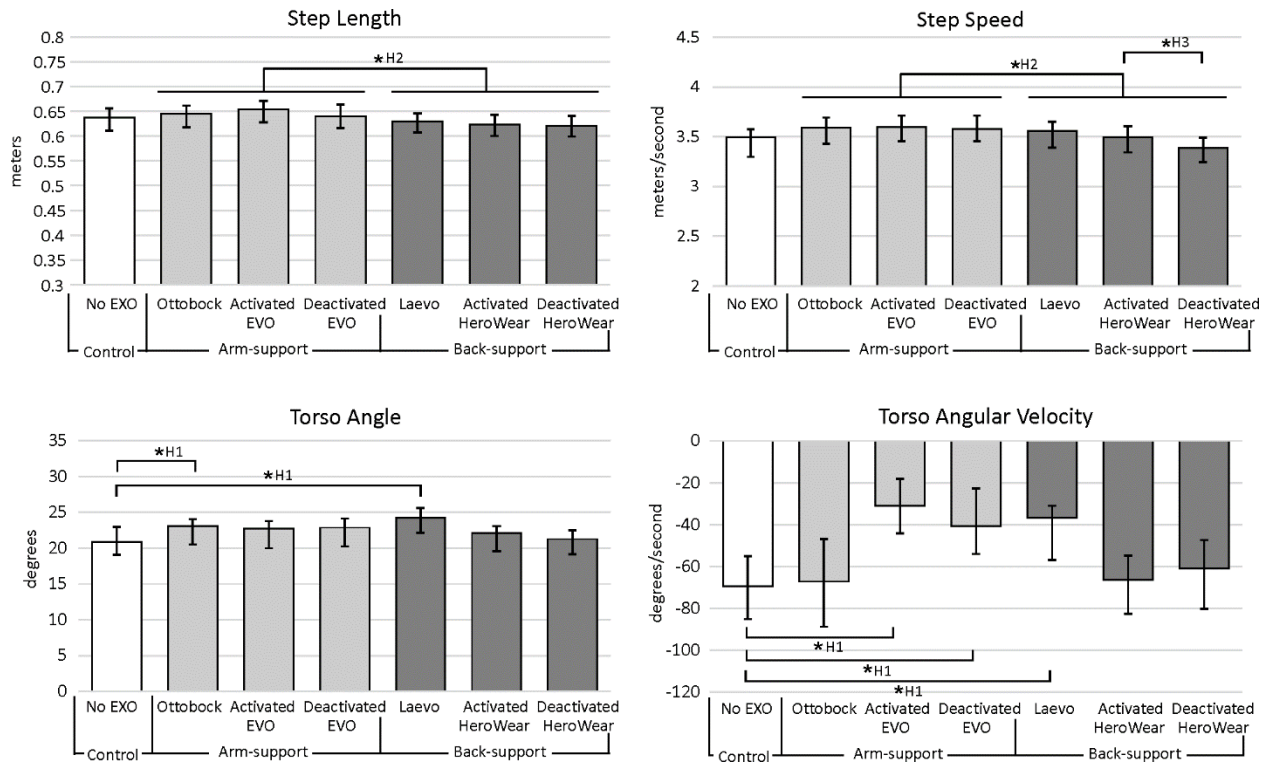
197 statistically significant differences. Torso angle was 2.2° larger with the Ottobock Shoulder (arm-  
 198 support;  $p < 0.034$ ) and 3.3° larger with the Laevo FLEX (back-support;  $p < 0.001$ ) when  
 199 compared to the no-EXO condition. Torso angular velocity was 38°/s slower in torso extension  
 200 with the Ekso EVO (arm-support;  $p = 0.005$ ) and 33°/s slower in torso extension with the Laevo  
 201 FLEX (back-support;  $p = 0.038$ ) when compared to the no-EXO condition. Regarding our  
 202 second hypothesis, step length was 2.2 cm shorter ( $p < 0.001$ ) and step speed was 10.8 cm/s  
 203 slower ( $p < 0.001$ ) with the back-support EXOs than with the arm-support EXOs. Regarding our  
 204 third hypothesis, step speed was 10.5 cm/s faster with the HeroWear Apex (back-support)  
 205 activated than with it deactivated ( $p = 0.020$ ). No other effects that addressed our hypotheses  
 206 were statistically significant (Table 2; Figure 3; and effect sizes are reported in the  
 207 Supplementary Material).

208  
 209  
 210

211 Table 2. Statistical results of kinematic variables of reactive balance after trips. Entries are  $p$   
 212 values from ANOVAs with \* indicating  $p \leq 0.05$ .

	Mass	Height	Order	Trial	Sex	Condition	Speed	Sex* Condition	Speed* Condition	Sex* Speed	Sex*Speed* Condition
<b>Step Length</b>	0.019*	0.111	0.252	0.508	0.131	<0.001*	<0.001*	0.288	0.289	<0.001*	0.692
<b>Step Speed</b>	0.043*	0.310	<0.001*	0.598	0.664	<0.001*	<0.001*	0.226	0.615	0.595	0.465
<b>Torso Angle</b>	0.653	0.129	<0.001*	0.906	0.403	<0.001*	<0.001*	0.083	0.930	<0.001*	0.270
<b>Torso Angular Velocity</b>	0.080	0.463	0.255	0.065	0.010*	<0.001*	<0.001*	0.889	0.090	0.305	0.337

213  
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215

216

217 Figure 3. Kinematic variables of reactive balance after trip-like perturbation in each of the seven  
 218 experimental conditions. Columns indicate least squares means and error bars indicate 95%  
 219 confidence intervals. Note that some y-axes do not start at zero; rather, scales were used to  
 220 represent typical variable ranges. Torso angle was measured relative to standing with a positive  
 221 value indicating torso flexion (forward). A negative torso angular velocity indicated torso  
 222 extension. Horizontal lines labeled with \* indicate conditions, or groups of conditions, that  
 223 significantly differed ( $p \leq 0.05$ ). H1-H3 labels indicate which hypothesis corresponds to each  
 224 statistically significant result.

225

226 **Discussion**

227 The purpose of this study was to investigate the effects of passive arm- and back-support EXOs  
 228 on reactive balance after slip-like and trip-like perturbations on a treadmill. Recent evidence

229 suggests that a back-support EXO can increase fall risk by adversely affecting gait (Park et al.,  
230 2022a) and responses to large postural perturbations (Dooley et al., 2023; Park et al., 2022b).  
231 Additional evidence and understanding of any such adverse effects could increase awareness and  
232 lead to mitigation strategies. Our results showed that the EXOs investigated here did not  
233 significantly affect the probability of a failed recovery, but did affect several kinematic variables  
234 in a way that suggested greater difficulty in recovering balance.

235

236 Our first hypothesis was that arm- and back-support EXOs would adversely affect reactive  
237 balance compared to not wearing an EXO. This hypothesis was modestly supported. After slip-  
238 like perturbations, stepping toe position was 4.1 cm more posterior when using the activated  
239 Ekso EVO (arm-support) than when using no EXO. An earlier study reported that deviations in  
240 this measure when compared to successful balance recovery (or in the case of the current study,  
241 the no-EXO condition) can increase the likelihood of a failed recovery (Allin et al., 2018). After  
242 trip-like perturbations, torso angle increased 2.2 - 3.3° with the Ottobock (arm-support) and  
243 Laevo (back-support) EXOs, and torso angular velocity decreased in extension 32 - 38 %/s with  
244 the Ekso (arm-support) and Laevo (back-support). More broadly, after slip-like perturbations, the  
245 only adverse effect was how an arm-support EXO affected stepping. After trip-like perturbations,  
246 both arm-support EXOs and one back-support EXO adversely affected torso kinematics. Three  
247 mechanisms are proposed for these adverse effects. First, the added torso mass/inertia associated  
248 with EXO use may have increased the physical demands needed to arrest torso kinematics.  
249 Interestingly, the adverse effects on torso kinematics were seen with both arm-support EXOS  
250 that are worn mostly on the torso and only the back-support EXO with greater mass (Laevo).  
251 The adverse effects on torso kinematics were not seen with the HeroWear, which notably had the

252 least amount of mass among the four EXOs investigated. Second, mechanical constraints  
253 imposed by the back-support EXOs may have affected hip/low back movements and, as a result,  
254 torso kinematics. The assistive hip/back extension moment provided by back-support EXOs  
255 could also affect hip and torso kinematics, but our results with respect to our third hypothesis  
256 (see below) do not support this mechanism. Third, upper limb kinematics may have been  
257 affected by some EXOs. Such kinematics have important roles in reactive balance (Alissa et al.,  
258 2020; Lee-Confer et al., 2022) and could have, in turn, affected stepping and trunk kinematics.  
259 Unfortunately, upper limb kinematics were not recorded here.

260

261 Our second hypothesis was that reactive balance would differ between back-support EXOs and  
262 arm-support EXOs. This hypothesis was supported after slip-like and trip-like perturbations  
263 given the 2.0 - 2.2 cm shorter step length and 6.1 - 10.8 cm/s slower step speed with the back-  
264 support EXOs than with the arm-support EXOs. It was also supported after slip-like  
265 perturbations given that pelvis height was 0.66% of its standing height higher after 1.4 m/s  
266 perturbations and that stepping toe position was 2.4 cm more posterior with the arm-support  
267 EXOs than with the back-support EXOs. More broadly, using the back-support EXOs resulted in  
268 adverse effects in that the initial recovery step was shorter and slower, and hip height was lower  
269 (at the fastest perturbation speed), than when using the arm-support EXOs for both slip-like and  
270 trip-like perturbations. These results were consistent with earlier studies showing that a back-  
271 support EXO not investigated here impeded hip flexion when stepping after laboratory-induced  
272 forward losses of balance (Park et al., 2022b) and during gait (Park et al., 2022c). Regarding the  
273 potential mechanisms for these effects, it may be because the back-support EXOs impeded hip  
274 flexion during forward stepping after trip-like perturbations and the initial hip flexion to help

275 elevate the foot off the treadmill belt prior to hip extension to step backward after slip-like  
276 perturbations.

277

278 Our third hypothesis was that reactive balance would differ between wearing an activated EXO  
279 and a deactivated EXO. While multiple differences were found that support this hypothesis,  
280 these differences were interpreted to be a mix of adverse and beneficial to reactive balance. After  
281 slip-like perturbations, activation of the Ekso EVO (arm-support) moved the stepping toe  
282 position 2.6 cm more posterior (presumably an adverse effect) and increased pelvis height by  
283 0.64% (beneficial effect). Additionally, after trip-like perturbations, activation of the HeroWear  
284 Apex (back-support) increased step speed by 10.5 cm/s (beneficial effect). The mechanisms  
285 behind these effects were unclear given that the activated HeroWear provides an assistive  
286 hip/low back extension moment yet step speed after trip-like perturbations involve hip flexion.  
287 Moreover, upper extremity kinematics were not collected so any changes with Ekso EVO  
288 activation could not be identified.

289

290 Several study limitations warrant consideration. First, the use of a 5x5 Latin square with 28  
291 participants meant the order of presentation of EXO conditions was not fully balanced across all  
292 participants. However, including the presentation order as a blocking factor in our statistical  
293 model minimized potential confounding related to order effects (see online Supplementary  
294 Material). Second, it is unclear how well our results based on repeated slip-like and trip-like  
295 treadmill perturbations generalize to slips or trips while walking over-ground. However, some  
296 generalization is expected given that prior studies using identical treadmill perturbations for  
297 balance training reported beneficial effects on slips and trips while walking over-ground (Allin et

298 al., 2020; Grabiner et al., 2012), and since the biomechanical mechanisms of a failed recovery  
299 after trip-like treadmill perturbations are the same as over-ground trips (Owings et al., 2001).  
300 Third, participants only wore the EXOs for a short period of time and additional usage may  
301 allow some accommodation that influences their effects on reactive balance.

302

303 In conclusion, arm-support and back-support EXOs did not increase the probability of a failed  
304 recovery after slip-like and trip-like perturbations, but several effects on kinematic variables  
305 suggest the EXOs increased the difficulty of balance recovery. These effects were likely due to  
306 the added mass and mechanical constraints imposed by the EXOs on hip/low back movements  
307 and possibly upper limb movements. Additional research is needed to confirm these  
308 mechanisms, which may lead to strategies for EXO developers to mitigate their adverse effects.  
309 The results of the current study suggest that, at least, caution is warranted when using these  
310 devices due to a potential increase in the risk of slip- and trip-induced falls.

311

312

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322

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324

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