Journal of Biomechanics 151 (2023) 111533

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

A passive leg-support exoskeleton adversely affects reactive balance after simulated slips and trips on a treadmill

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ARTICLE INFO

Keywords:
Exoskeleton
Trip
Slip
Balance recovery
Falls

ABSTRACT

Occupational exoskeletons have become more prevalent as an ergonomic control to reduce the physical demands of workers. While beneficial effects have been reported, there is relatively little evidence regarding potential adverse effects of exoskeletons on fall risk. The purpose of this study was to investigate the effects of a leg-support exoskeleton on reactive balance after simulated slips and trips. Six participants (three females) used a passive, leg-support exoskeleton that provided chair-like support in three experimental conditions (no exoskeleton, low-seat setting, high-seat setting). In each of these conditions, participants were exposed to 28 treadmill perturbations from an upright standing posture simulating a backward slip (0.4–1.6 m/s) or a forward trip (0.75–2.25 m/s). The exoskeleton increased the probability of a failed recovery, and adversely affected reactive balance kinematics, after simulated slips and trips. After simulated slips, the exoskeleton decreased initial step length 0.039 m, decreased mean step speed 0.12 m/s, anteriorly displaced touchdown position of the initial recovery step by 0.045 m, and decreased PSIS height at initial step touchdown by 1.7 % sof its standing height. After simulated trips, the exoskeleton increased trunk angle at step 2.4 degrees, and decreased initial step length 0.033 m. These effects appeared to result from the exoskeleton inhibiting regular stepping motion due to its posterior placement on the lower limbs, added mass, and mechanical constraints on participant movement. Our results suggest care may be needed among leg-support exoskeleton users when at risk of slips or trips and motivate potential exoskeleton design modifications to reduce fall risk.

1. Introduction

Passive leg-support exoskeletons (EXOs) targeting occupational applications provide knee support while squatting, or chair-like support when assuming a seated posture. Prior studies have generally found a reduction in lower limb muscle activity during their use. For example, when using this type of EXO for chair-like support, lower limb muscle activity decreased 36 % during a simulated bolting task at two heights (Kong et al., 2022), and the percentage of body weight supported by the feet decreased 64 % and gastrocnemius muscle activity decreased 75 % compared to standing during a simulated seated assembly task (Luger et al., 2019). Leg-support EXOs can also result in unintentional and undesirable outcomes related to balance or fall risk such as a greater susceptibility to losses of balance after external perturbations during simulated seated assembly work (Steinhilber et al., 2022), and a reduced “feeling of safety” while walking on a treadmill (Groos et al., 2020).

Leg-support EXOs may also impair stepping responses after slipping or tripping due to their added mass, imposed mechanical constraints, or resistance to movement. This effects may, in turn, increase fall risk. While we are not aware of any studies of leg-support EXOs on gait or reactive stepping, two studies of a back-support EXO showed adverse effects on stepping. Park et al. (2022a) reported a decrease in step length, and an increase in step width and step variability while walking with a back-support EXO. Similarly, Park et al. (2022b) reported a decrease in hip flexion range of motion and angular velocity, hip and knee flexion velocity, step length, and margin of stability when stepping upon release from a static forward lean with a back-support EXO.

The purpose of this exploratory study was to investigate the effects of a passive leg-support EXO (Chairless Chair®, noone, Germany) on reactive balance after simulated slips and trips. This EXO provides chair-like support when assuming a (semi)seated posture (Fig. 1). We hypothesized that this leg-support EXO would adversely affect reactive balance after simulated slips and trips. This hypothesis was based upon the EXO locking mechanism providing a mechanical constraint/resistance to stepping and added mass potentially limiting knee range of motion and initial step length during reactive stepping. We also

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https://doi.org/10.1016/j.jbiomech.2023.111533
Accepted 3 March 2023
Available online 6 March 2023

hypothesized that this leg-support EXO would have a greater adverse effect on reactive balance as perturbation speed/intensity increased. This hypothesis was based upon faster perturbations requiring faster and longer stepping responses that are more likely to be limited by an EXO. Results from this study may help justify warnings of increased fall risk among exoskeleton users and motivate potential exoskeleton design modifications to reduce such risk.

2. Methods

Six young adults were recruited from the university population and completed the study (three females: mean ± standard deviation age = 21.7 ± 1.5 years; height = 1.65 ± 0.12 m; mass = 63.3 ± 4.5 kg; three males: age = 22.7 ± 2.1 years; height = 1.75 ± 0.05 m; mass = 80.7 ± 13.2 kg). Participants were required to be 18–30 years old, have a body mass index<30 kg/m^2, have no recent (past 12 months) or current injuries that affected their balance or daily activities, and not be pregnant. This study was approved by the university Institutional Review Board, and all participants provided written consent prior to participation.

Each participant was tested in three experimental conditions presented in counter-balanced order using two 3 × 3 balanced Latin Squares: 1) wearing no EXO; 2) wearing the EXO in a low-seat setting; and 3) wearing the EXO in a high-seat setting. This EXO provides chair-like support with the user able to select over a continuous range the height at which this support is engaged. The low-seat setting used here was the lowest height over the continuous range, and the high-seat setting was the highest height over the continuous range (mimicking a taller chair than the low-seat setting). Note that this EXO has no "off" setting such that a user could wear it and not receive support. Within each experimental condition, the participant was exposed to 28 treadmill perturbations (Fully Instrumented Treadmill, Bertec, Columbus, OH) including two trials at each of 14 speeds/directions described below. The order of presentation of these 28 perturbations within each condition was randomized.

Stance-slip and stance-trip perturbations were used to simulate slipping and tripping as in prior work (e.g., (Bieryla et al., 2007; Dusane et al., 2019; Owings et al., 2001; Yang et al., 2018). Prior to each perturbation, the participant stood upright on the stationary treadmill belt in standardized footwear. The participant was reminded to stay relaxed and was asked to count out loud backwards by three from a random 2-digit number provided by the investigator. After a random 1–5 s delay, the treadmill belt underwent a step increase in speed (in under 150 ms) to a constant speed, requiring a stepping response to recover balance and establish a stable gait. Slip-like perturbations involving a backward loss of balance were induced by abrupt changes in speed from 0 m/s to 0.4–1.6 m/s forward in increments of 0.2 m/s. Trip-like perturbations involving a forward loss of balance were induced by abrupt changes in speed from 0 m/s to 0.75–2.25 m/s backward in increments of 0.25 m/s. Differences in forward and backward speeds and increments were used to account for the greater difficulty in recovering from forward belt movements and to maintain seven levels of speed in both directions. After the participant reached a stable gait or was fully supported by a safety harness affixed by a lanyard to an overhead gantry, the treadmill belt was slowed to 0 m/s to end the trial. Lanyard length was set so that the participant's knee was 10 cm above the treadmill belt when trying to kneel. Prior to testing, participants donned the EXO, moved their hips and knees through their ranges of motion to feel the EXO influence, and sat in the EXO on both the high and low seat settings to feel how the mechanism locked and provided support. Testing then commenced without any practice trials. A 10-minute rest break was provided between conditions.

Whole-body kinematics were sampled at 100 Hz (10 Vero cameras, Vicon, Centennial, CO, USA) from reflective markers (see supplementary file for locations). Ground reaction forces were sampled at 1000 Hz from force plates integrated in the treadmill. Forces applied to the harness were sampled at 1000 Hz using a load cell (ATO Inc., Diamond Bar, CA, USA) in-line with the lanyard. Video recordings of all perturbations were also obtained (GoPro HERO8, San Mateo, CA, USA). Kinematic and force

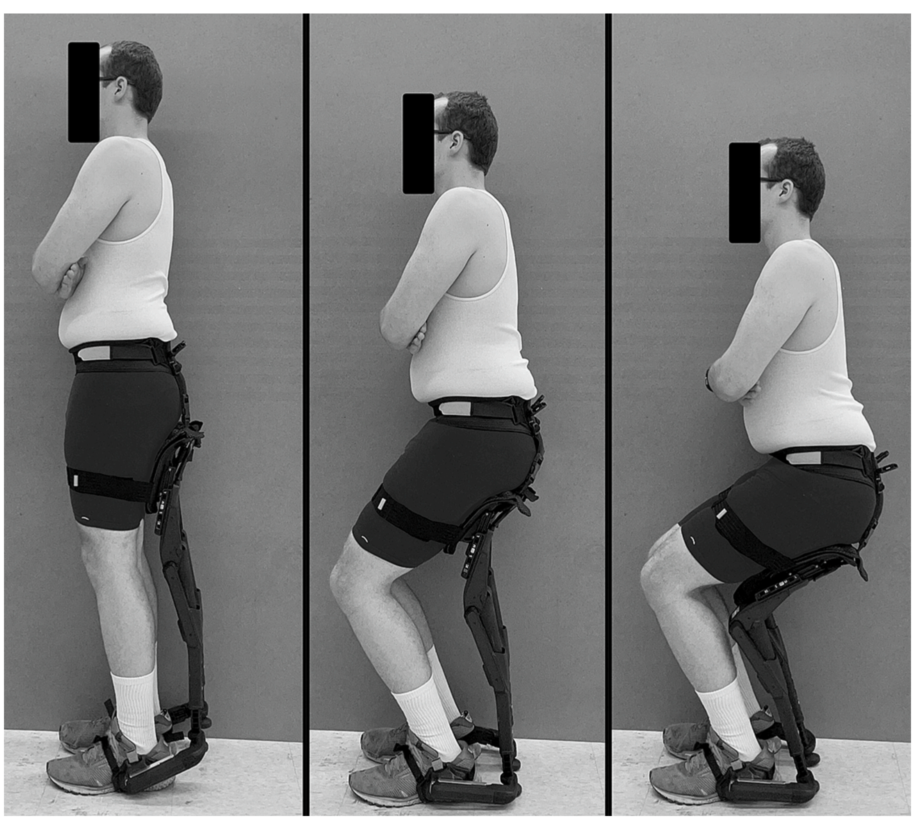

Fig. 1. Photographs of a user wearing the EXO while standing (left), in the high-seat setting (middle), and in the low-seat setting (right).

data (from force plate and harness load cell) were low-pass filtered (4th order, bi-directional, Butterworth) at 10 and 300 Hz, respectively (Schreven et al., 2015).

Our primary dependent variable was perturbation outcome, either a successful or failed recovery, with the latter determined when the force applied to the harness exceeded 30 % of body weight (Yang and Pai, 2011). Secondary dependent variables were measures of trunk and stepping kinematics to provide insight on the mechanisms responsible for failed recoveries (Allin et al., 2018; Brodie et al., 2018; Owings et al., 2001). These measures were determined in the anterior-posterior (AP) plane and at touchdown of the initial recovery step (i.e., when vertical ground reaction force exceeded 5 N). For simulated slips, the measures were step length, mean step speed, AP position of the stepping toe relative to the PSIS (proxy measure of pelvis position), and height of the PSIS. For simulated trips, the measures were trunk angle, step length, and mean step speed, with trunk angle defined using a line connecting the midpoint of the shoulder markers to the midpoint of the hip markers, projected onto a mid-sagittal plane and relative to standing.

Separate generalized logistic regression models were used to explore the effects of condition, perturbation speed, and the condition × speed interaction on the probability of successful recovery after simulated slips and trips. Sex was excluded from these analyses since it prevented the regression models from converging. Mixed-factor analyses of variance (ANOVAs) were used to investigate the effects of the same factors, plus sex, on each of the slip and trip kinematic measures. While sex was not a factor of high interest, it was included to account for more variability in the data and therefore improve our ability to find effects of other factors of greater interest. The order of presentation of the three conditions was also included as a blocking factor. Trials were excluded from ANOVA analyses if harness support exceeded 30 % body weight prior to touchdown of the initial recovery step (3 of 504 trials), or if the stepping foot never lifted above the belt, making step timing difficult to discern (16 trials of 504 trials). Body mass and height were not included because preliminary analyses indicated neither was a significant covariate. Trunk angle required a square root transformation to address heteroscedasticity, though untransformed data are reported for utility. Tukey's HSD was used for *post hoc* pair-wise comparisons when needed. All statistical analyses were performed using JMP Pro 16.0 (SAS Institute Inc., Cary, NC, USA) with statistical significance concluded when $p \leq 0.05$. Given the exploratory nature of the study, effects that approached significance ($0.05 < p \leq 0.10$) were also highlighted.

3. Results

After simulated slips, the EXO adversely affected reactive balance, particularly in the high-seat condition. The probability of a failed slip recovery was significantly affected by the condition and speed (Fig. 2). The high-seat and low-seat settings exhibited odds ratios of 11.78 and 2.85, respectively, for a failed recovery compared to the no EXO condition (assuming that the slip speed is 1.2 m/s). In addition, the probability of a failed slip recovery was significantly affected by speed with the odds increased by 82.16 for each 1 m/s increase in speed. Kinematic measures showed no condition × speed interactive effects but did show main effects of condition and speed (Table 1 and Supplementary Material). Step length was 3.9 cm shorter in the high-seat setting than with no EXO ($p = 0.19$). Mean step speed was 0.12 m/s slower in the high-seat setting than with no EXO ($p = 0.002$). The stepping toe was positioned 4.5 cm more anterior to the PSIS at step in the high-seat setting than with no EXO ($p = 0.003$). Height of the PSIS at step was 1.7 % of standing height (SH) lower in the high-seat setting than with no EXO ($p < 0.001$), and 1.7 %SH lower in the low-seat setting than with no EXO ($p < 0.001$).

After simulated trips, the EXO also adversely affected reactive balance, particularly in the high-seat condition. The probability of a failed trip recovery was significantly affected only by speed with the odds increased by 17.6 for each 1 m/s increase in speed (Fig. 3). Kinematic measures showed no condition × speed interactive effects but did show main effects of condition and speed (Table 1 and Supplementary Material). Trunk angle at step was 2.4 deg larger in the high-seat setting than with no EXO ($p = 0.001$). Step length was 3.3 cm shorter in the high-seat setting than with no EXO ($p = 0.002$). Mean step speed

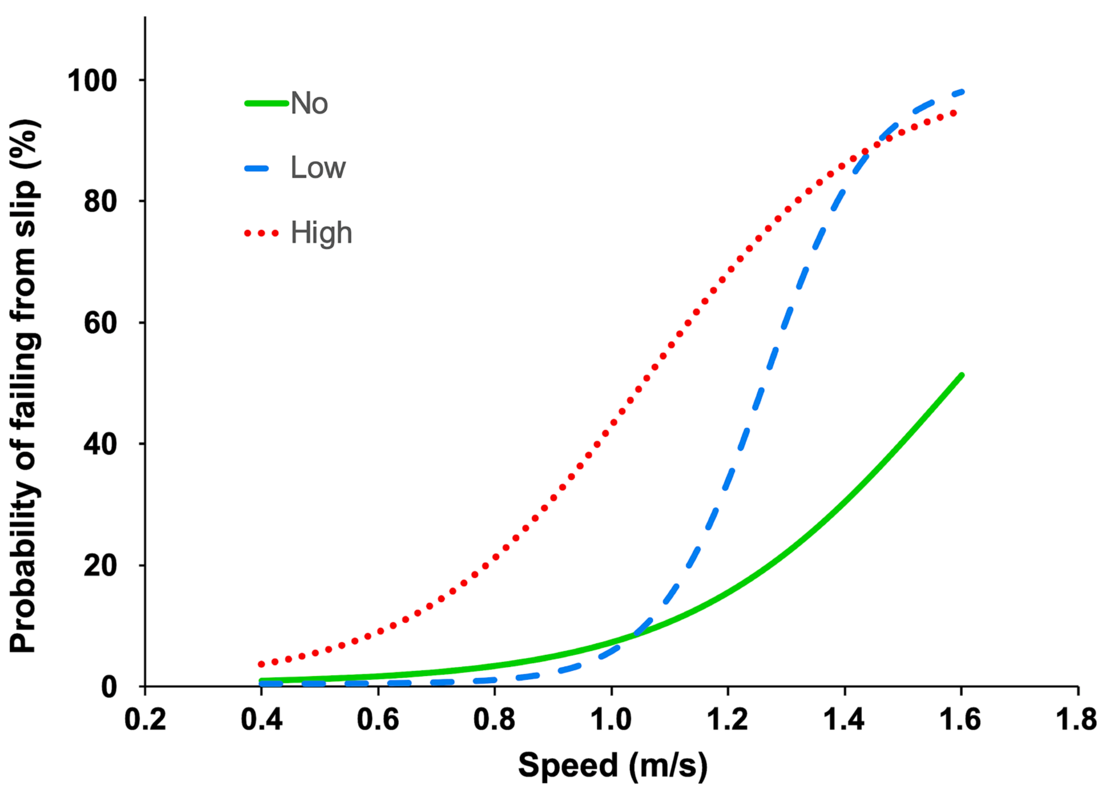

Fig. 2. Probability of a failed recovery after a simulated slip as predicted from logistic regression analysis.

Table 1
Summary of ANOVA results for kinematic measures of reactive balance. Entries are p values, and significant effects are indicated with *. The "i" superscript indicates an increase in the dependent variable when speed increased, and the "d" superscript indicates a decrease. Summary measures and effect sizes are provided in the Supplementary Material.

Dependent Variable	Condition (C)	Speed (S)	C × S	Sex
Simulated slips				
Step length	0.024*	<0.001*^{i}	0.157	0.631
Mean step speed	0.003*	<0.001*^{d}	0.152	0.929
AP distance between PSIS and toe at step	0.003*	<0.001*^{d}	0.116	0.841
PSIS height at step	<0.001*	<0.001*^{d}	0.843	0.487
Simulated trips				
Trunk angle at step†	0.002*	<0.001*^{i}	0.665	0.042*
Step length	0.002*	<0.001*^{i}	0.326	0.635
Mean step speed	0.064	<0.001*^{d}	0.187	0.628

† Indicates the variable required a square root transformation prior to statistical analysis to address heteroskedasticity.

approached significance with values in the low-seat setting being slower than with no EXO ($p = 0.083$). The only main effect of sex was that females exhibited a 7.9 deg larger trunk angle at step than males ($p = 0.042$).

4. Discussion

The purpose of this study was to investigate the effects of a leg-support EXO on reactive balance after simulated slips and trips. Our first hypothesis, that the EXO would adversely affect reactive balance, was supported for both slips and trips. After slipping, the EXO increased the probability of failed recovery, and adversely affected kinematic measures as indicated by a shorter step length, slower step, more anteriorly positioned stepping foot at step despite a backward loss of balance, and a lower PSIS at step. After tripping, the EXO had less of an adverse effect in that probability of failed recovery was not affected, but trunk angle was larger, step length was shorter, and step speed was slower (albeit not a significant effect). While we are not aware of any studies of leg-support EXOs on gait or reactive stepping, a back-support EXO has been similarly reported to decrease step length, hip flexion range of motion, and hip and knee flexion angular velocities during balance recovery, due to the extension torque generation about the hip (Park et al., 2022b).

We believe there are two primary reasons for the adverse effects found here. First, the leg-support EXO investigated here is worn on the posterior aspect of the lower limbs (Fig. 1). This posterior positioning appears to be unique among leg support EXOs (exoskeletonreport.com), and frequently resulted in inadvertent ground contact of the rubber cap on the base of the EXO when a participant was falling backward and attempting to step backward to recover balance with lowered hips. This ground contact prevented stepping and led to many failed slip recoveries. Such ground contact occurred more often on the high-seat setting because the locking mechanism limits knee flexion to a greater extent than the low-seat setting. Future work should investigate other leg supports EXOs that are not positioned posteriorly on the lower limb. Second, the added mass and mechanical constraint/resistance imposed by the EXO may have contributed to a decreased step length and slower step speed. These changes, in turn, could have led to a lower PSIS height at step after simulated slips and an increased trunk angle at step after simulated trips. The mechanical constraint is at least partly due to the flexion/extension rotational axes of the EXO differing from the axes of the hips and knees, which also has been implicated in changes in hip and knee angles when children wear a knee brace during gait (Rossi et al., 2013).

Our second hypothesis, that the EXO would have a greater adverse effect on reactive balance as perturbation speed increased, was supported for both slips and trips as well. The odds of failed recoveries with EXO use increased with perturbation speed after simulated slips and trips. However, the reasons for this were not clear, because none of the measures of response kinematics that help explain the mechanism behind the failed recoveries exhibited a condition × speed interaction.

Several study limitations warrant consideration. First, given the exploratory nature of this study, our sample size was small and limited to young working-age adults. This limits confidence in generalizing the results to the working population and to older workers. Moreover, the relatively small sample size precluded strong conclusions regarding sex differences. Second, simulated slips and trips on a treadmill were utilized to provide greater experimental control than slipping or tripping while walking over ground. The similarity between these simulated

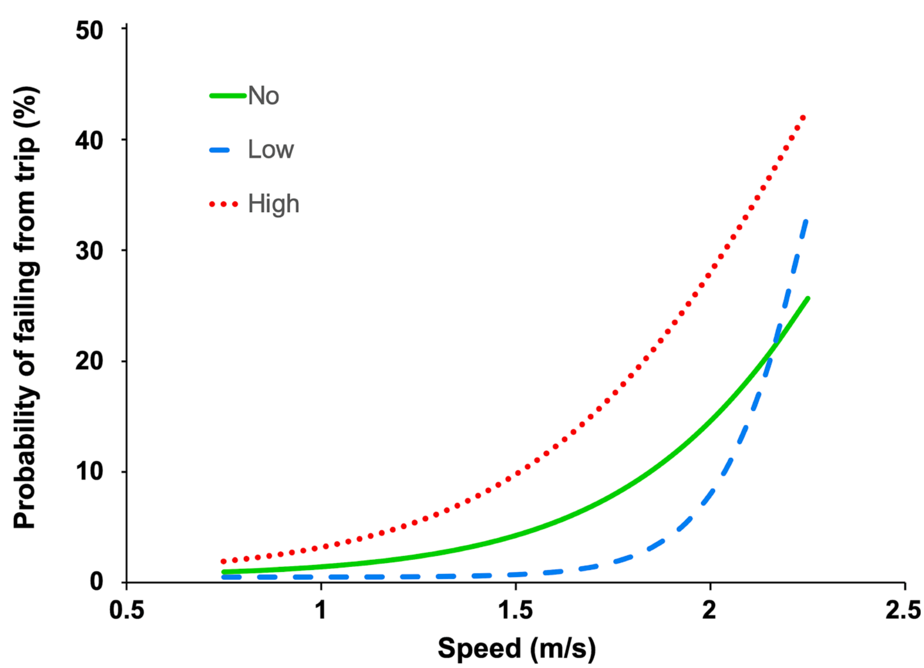

Fig. 3. Probability of a failed recovery after a simulated trip as predicted from logistic regression analysis.

slips/trips and actual slips/trips while walking over ground is supported by studies showing that repeated exposure to the former can improve reactive balance after the latter (Bieryla et al., 2007; Dusane et al., 2019; Owings et al., 2001; Yang et al., 2018). Third, we did not use a tripping obstacle, and the need to step initially over a trip obstacle may exacerbate the adverse effects of the EXO. Fourth, our participants only wore the EXO for a few minutes prior to testing, and added experience with the EXO may influence its effects on reactive balance. Ringhof et al. (2019) reported adverse effects of a leg-support EXO on non-stepping reactive balance in response to abrupt support surface translations and hypothesized that altered neuromuscular control from additional EXO use may be required. However, we do not expect that the movement limitations imposed by the EXO here would be eliminated with additional experience or altered neuromuscular control. Fifth, because the EXO does not allow its use without support, we were unable to evaluate the effects of only its added mass. Our discussion of mechanisms of its adverse effects are therefore speculative.

In conclusion, using a leg-support EXO adversely affected reactive balance after simulated slips and trips. These adverse effects were likely due to the EXO contacting the ground during backward stepping with the hips lowered. The added mass and mechanical constraints on stepping imposed by the EXO may also have contributed to its adverse effects on reactive balance, but these mechanisms remain speculative. Our results suggest caution is warranted when using these devices in some applications due to a potential increase in the risk of slip and trip-induced falls, and may inform design improvements to mitigate the adverse effects reported here.

CRediT authorship contribution statement

Stephen Dooley: Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Visualization, Investigation, Methodology. **Sunwook Kim:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Maury A. Nussbaum:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Michael L. Madigan:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

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.

Acknowledgements

This research was supported in part by a grant from the U.S. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health to the Johns Hopkins Education and Research Center for Occupational Safety and Health (award number T42 OH0008428). The funding source did not contribute to the design or conduct of the study, analysis or interpretation of results, manuscript preparation, or the decision to submit the manuscript for publication. We would like to thank Sydney Kelley for her assistance during data collection, and Randy Waldron for his assistance in fabricating the experimental setup.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111533.

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Supplementary Material for

A passive leg-support exoskeleton adversely affects reactive balance after simulated slips and trips on a treadmill

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Table S1. Statistical results for Initial Step Length after slipping. * indicates $p < 0.05$.

	***F* Ratio**	***p* value**	**η^2 (eta squared)**
Condition	3.976	0.021 *	0.047
Slip Speed	20.241	<0.001 *	0.723
Condition x Slip Speed	1.409	0.166	0.101
Sex	0.264	0.634	0.008

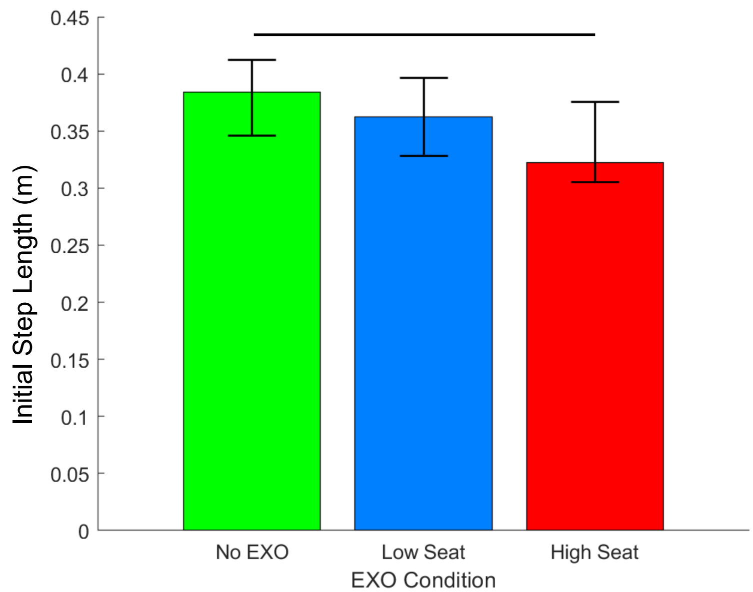

Figure S1a. Initial Step Length after slipping by EXO Condition (means and error bars indicate 95% confidence intervals). The horizontal line connects conditions that differed.

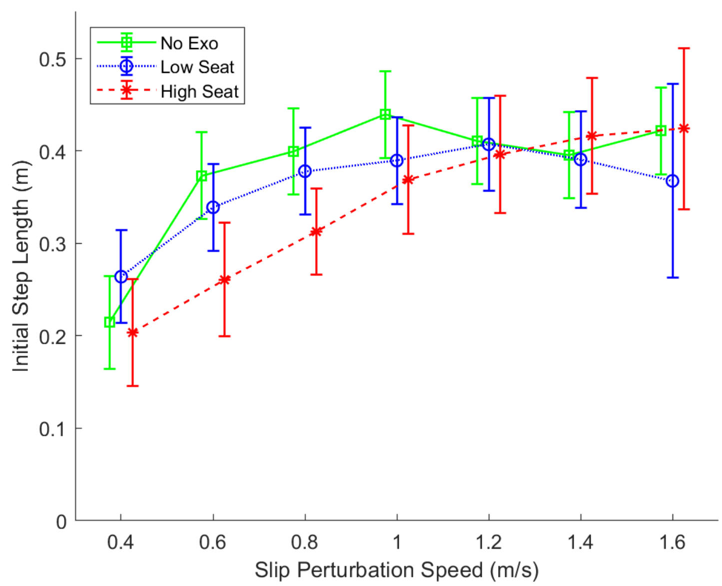

Figure S1b. Initial Step Length after slipping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S2. Statistical results for Mean Step Speed after slipping. * indicates $p < 0.05$.

	***F* Ratio**	***p* value**	**η^2 (eta squared)**
Condition	6.092	0.003 *	0.073
Slip Speed	34.385	<0.001 *	1.228
Condition x Slip Speed	1.427	0.158	0.102
Sex	0.008	0.935	0.001

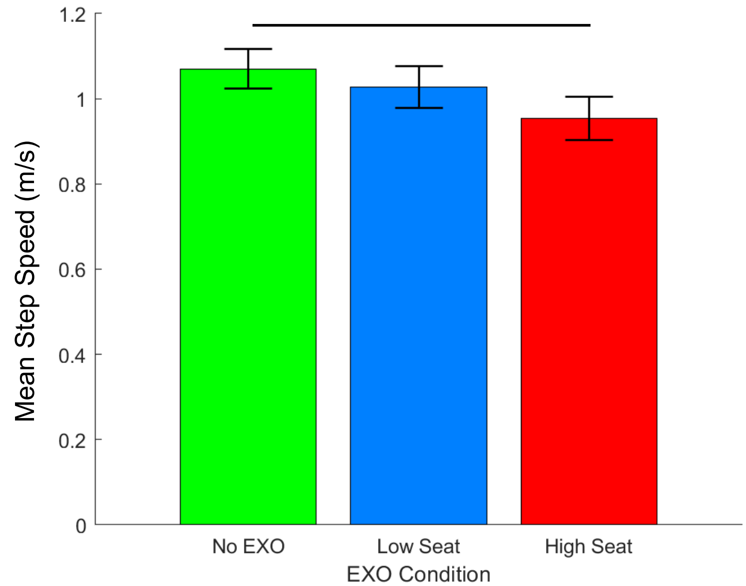

Figure S2a. Mean Step Speed after slipping by EXO Condition (mean and error bars indicate 95% confidence intervals). The horizontal line connects conditions that differed.

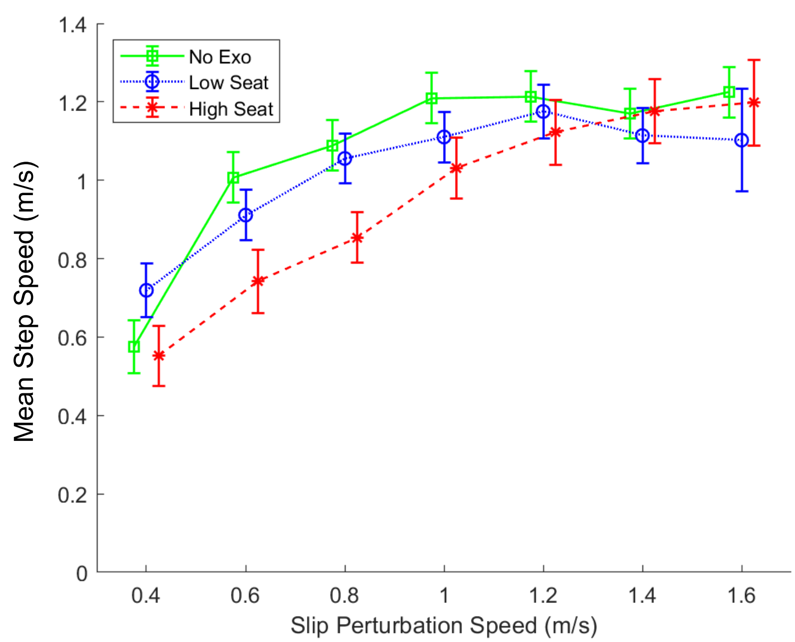

Figure S2b. Mean Step Speed after slipping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S3. Statistical results for Anterior-Posterior Distance Between PSIS And Toe At Step after slipping. * indicates $p < 0.05$.

	***F* Ratio**	***p* value**	**η^2 (eta squared)**
Condition	6.016	0.003 *	0.072
Slip Speed	19.239	<0.001 *	0.687
Condition x Slip Speed	1.522	0.121	0.109
Sex	0.047	0.839	0.004

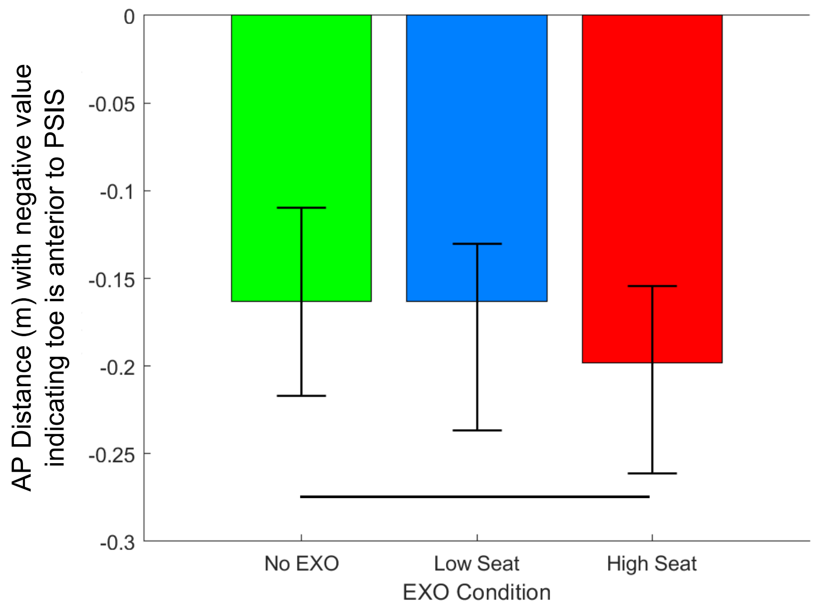

Figure S3a. Anterior-Posterior Distance Between PSIS And Toe At Step after slipping by EXO Condition (means and error bars indicate 95% confidence intervals). The horizontal line connects EXO Conditions that differed.

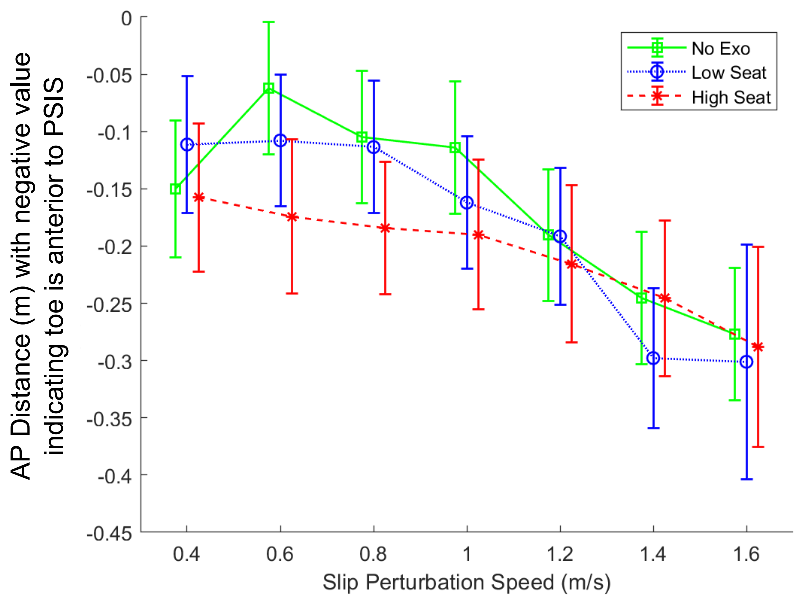

Figure S3b. Anterior-Posterior Distance Between PSIS And Toe At Step after slipping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S4. Statistical results for PSIS Height At Step after slipping. * indicates $p < 0.05$.

	F Ratio	p value	η^2 (eta squared)
Condition	16.023	<0.001 *	0.191
Slip Speed	92.769	<0.001 *	3.313
Condition x Slip Speed	0.602	0.839	0.043
Sex	0.537	0.503	0.024

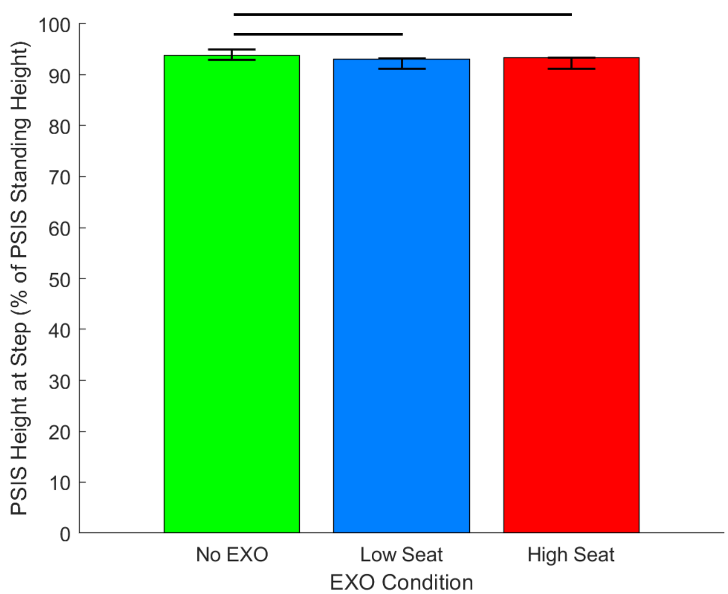

Figure S4a. PSIS Height At Step after slipping by EXO Condition (means and error bars indicate 95% confidence intervals). The horizontal lines connect conditions that differed.

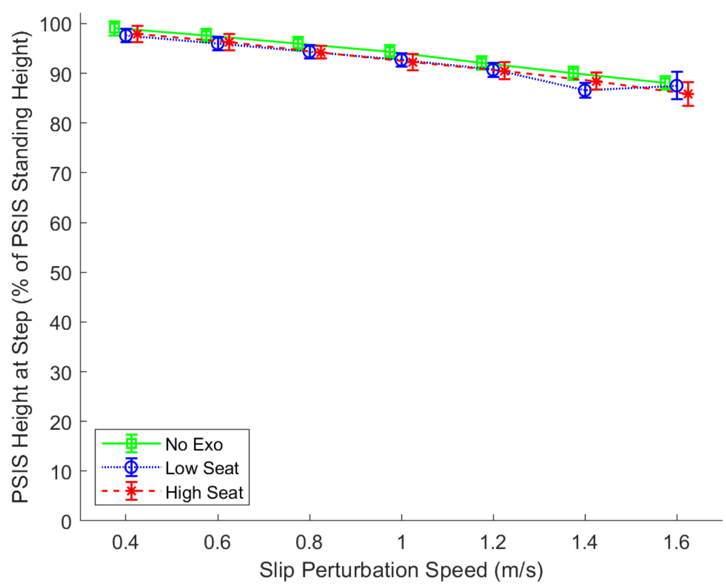

Figure S4b. PSIS Height At Step after slipping by Speed and EXO Condition (means and error bars indicate are 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S5. Statistical results for Trunk Angle at Step after tripping. * indicates $p < 0.05$.

	***F* Ratio**	***p* value**	**η^2 (eta squared)**
Condition	6.713	0.002 *	0.061
Trip Speed	83.985	<0.001 *	2.280
Condition x Slip Speed	0.782	0.669	0.042
Sex	8.971	0.040 *	0.949

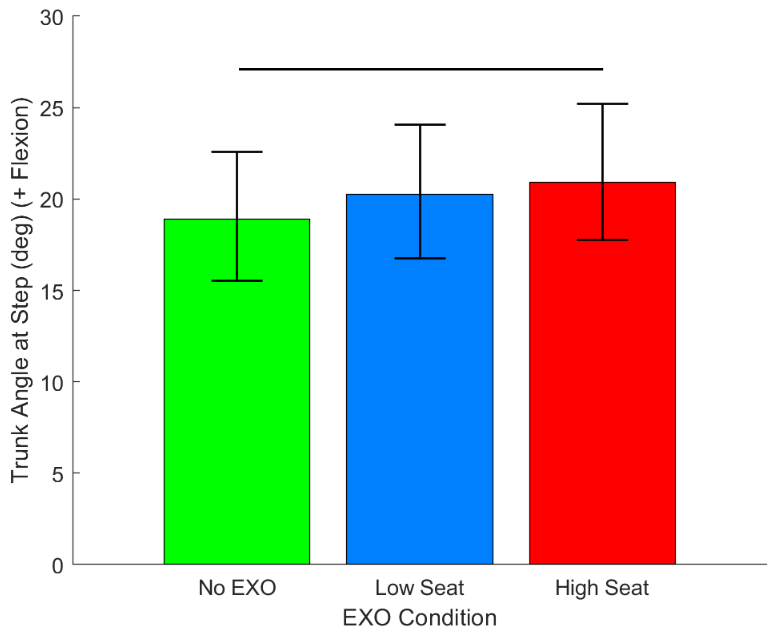

Figure S5a. Trunk Angle at Step after tripping by EXO Condition (means and error bars indicate 95% confidence intervals). The horizontal line connects conditions that differed.

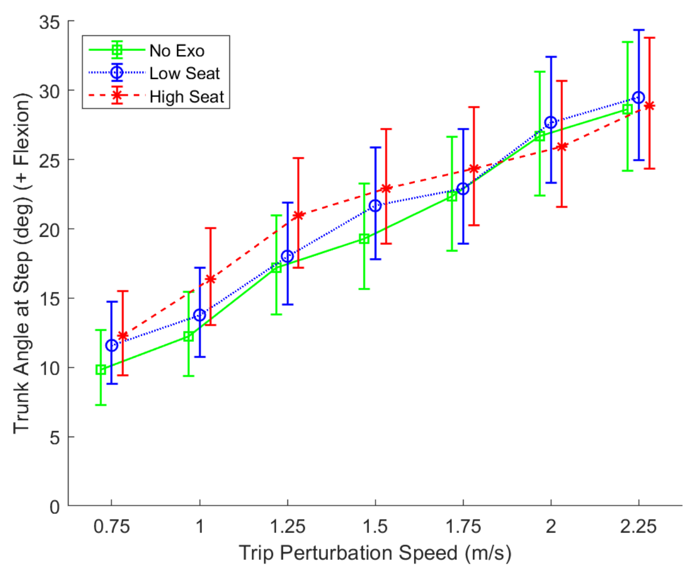

Figure S5b. Trunk Angle at Step after tripping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S6. Statistical results for Initial Step Length after tripping. * indicates $p < 0.05$.

	F Ratio	*p* value	η^2 (eta squared)
Condition	6.268	0.002 *	0.057
Trip Speed	177.553	<0.001 *	4.820
Condition x Slip Speed	1.145	0.326	0.062
Sex	0.262	0.636	0.108

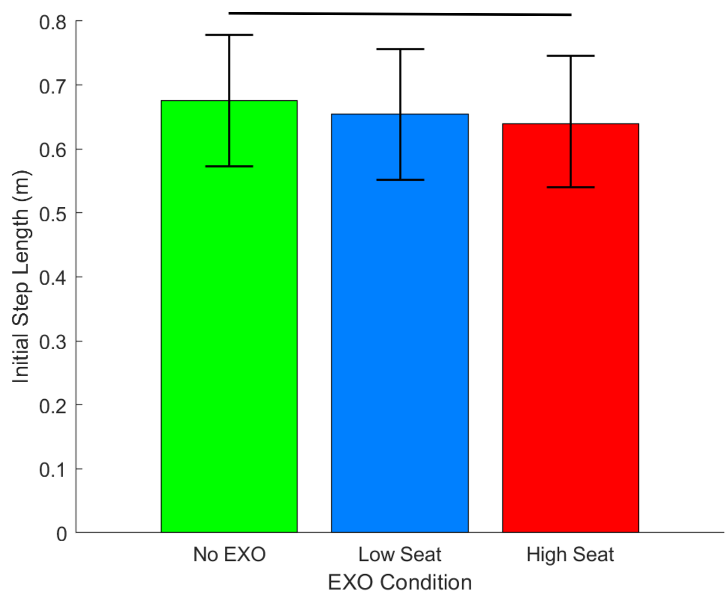

Figure S6a. Initial Step Length after tripping by EXO Condition (means and error bars indicate 95% confidence intervals). The horizontal line connects conditions that differed.

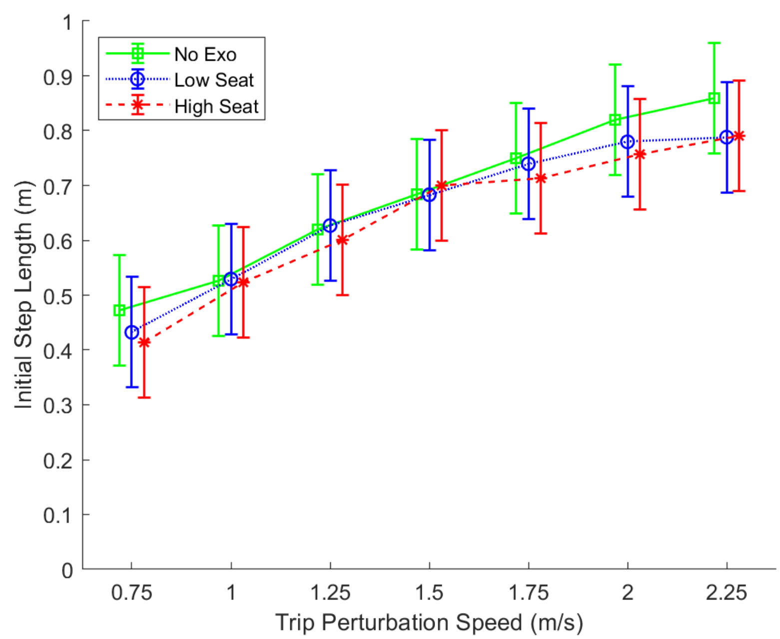

Figure S6b. Initial Step Length after tripping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.

Table S7. Statistical results for Mean Step Speed after tripping. * indicates $p < 0.05$.

	F **Ratio**	***p*** **value**	η^2 **(eta squared)**
Condition	2.786	0.064	0.070
Trip Speed	284.819	<0.001 *	7.732
Condition x Slip Speed	1.359	0.187	0.074
Sex	0.274	0.628	0.164

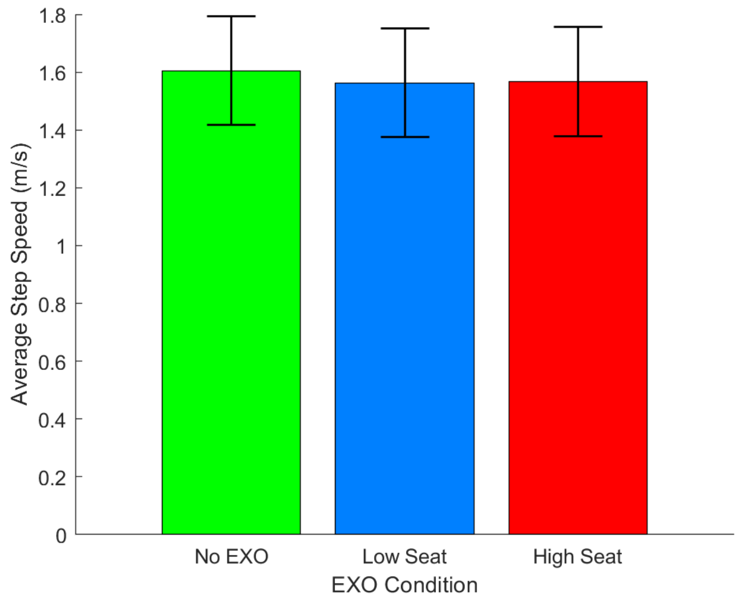

Figure S7a. Mean Step Speed after tripping by EXO Condition (means and error bars indicate 95% confidence intervals).

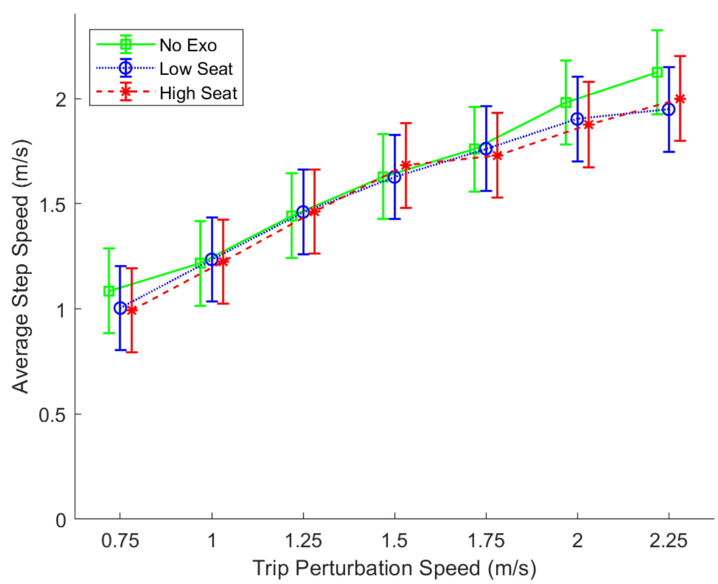

Figure S7b. Mean Step Speed after tripping by Speed and EXO Condition (means and error bars indicate 95% confidence intervals). Statistically significant pairwise comparisons were not indicated because this dependent variable did not exhibit an EXO Condition × Speed interaction, yet this figure is provided for completeness.