



A pilot study investigating motor adaptations when learning to walk with a whole-body powered exoskeleton

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ABSTRACT

Evidence is emerging on how whole-body powered exoskeleton (EXO) use impacts users in basic occupational work scenarios, yet our understanding of how users learn to use this complex technology is limited. We explored how novice users adapted to using an EXO during gait. Six novices and five experienced users completed the study. Novices completed an initial training/familiarization gait session, followed by three subsequent gait sessions using the EXO, while experienced users completed one gait session with the EXO. Spatiotemporal gait measures, pelvis and lower limb joint kinematics, muscle activities, EXO torques, and human-EXO interaction forces were measured. Adaptations among novices were most pronounced in spatiotemporal gait measures, followed by joint kinematics, with smaller changes evident in muscle activity and EXO joint torques. Compared to the experienced users, novices exhibited a shorter step length and walked with significantly greater anterior pelvic tilt and less hip extension. Novices also used lower joint torques from the EXO at the hip and knee, and they had greater biceps femoris activity. Overall, our results may suggest that novices exhibited clear progress in learning, but they had not yet adopted motor strategies similar to those of experienced users after the three sessions. We suggest potential future directions to enhance motor adaptations to powered EXO in terms of both training protocols and human-EXO interfaces.

1. Introduction

Powered/active exoskeletons – wearable systems to support and/or enhance the wearer during various physical activities – have generated substantial interest as a new intervention to control work-related musculoskeletal disorders (WMSDs) in various workplaces. On-body assistance provided by an exoskeleton offers unique potential benefits in that wearing an exoskeleton could improve work performance while not limiting mobility. Exoskeleton technologies also have great application potential for vulnerable populations such as the elderly, allowing such workers to complete tasks that they may not otherwise be able to perform (Davis et al., 2020). Powered exoskeletons are still largely in the research and development stages (e.g., Otten et al., 2018; Poliero et al., 2020; Sankai, 2011; Stadler et al., 2017; Zoss et al., 2006), although a few have already entered the commercial market (e.g., HAL®, Cray X, Roam Robotics). A few human-in-the-loop experiments have examined the effects of powered exoskeleton use for different occupational tasks. Powered back-support exoskeletons, such as RoboMate and HAL®, have been found to respectively reduce trunk extensor muscle activity by up

to ~ 15% during simulated lifting (Huysamen et al., 2018) and up to ~ 20% during repetitive symmetric lifting (von Glinski et al., 2019). Some research prototypes have also been reported to reduce physical workload in the arms (Otten et al., 2018) and back (Poliero et al., 2020). We recently reported that using a whole-body powered exoskeleton reduced trunk and leg muscle activities during both stationary and ambulatory load handling tasks (Park et al., 2022). These studies show the potential beneficial effects of powered exoskeletons in mitigating physical demands during industrial work tasks.

However, powered exoskeletons can generate variable patterns of assistance/support as a function of task context and/or human states, potentially resulting in complex human-exoskeleton interactions. Hence, to enhance the safe and effective adoption of powered exoskeletons and their usability, there is an important need for a better understanding of how humans learn/alter their motor coordination strategies over time when using powered exoskeletons (Jacobs et al., 2018; Steele et al., 2017). Yet, knowledge in this area remains limited (Uchida et al., 2016).

Human motor adaptation to exoskeletons has been explored

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extensively in the field of rehabilitation to understand how users alter their motor strategies/coordination when learning to use a joint-specific rehabilitation exoskeleton for the ankle (Galle et al., 2013; Gordon and Ferris, 2007; Jacobs et al., 2018; Kao and Ferris, 2009; Kao et al., 2010; Sawicki and Ferris, 2008) or the hip (Lewis and Ferris, 2011). Results from these studies have shown that participants can learn to walk more efficiently over time with an exoskeleton based on several metrics (e.g., muscle activity, joint kinematics, and/or metabolic measures). For example, Sawicki and Ferris (2008) examined adaptations to a powered ankle exoskeleton in terms of biomechanics and metabolic consumption over the three gait sessions and reported that users adapted to significantly reduce their soleus muscle activity and metabolic consumption by the third session. However, despite a few emerging studies like this, there is still no clear or broad consensus regarding the amount of training/exoskeleton exposure/time required for each user (even healthy individuals) to maximize the benefits of exoskeleton use.

For several reasons, it is unclear to what extent these earlier studies on rehabilitation exoskeleton use can directly apply to powered industrial exoskeleton use. First, there is an underlying difference in assistance strategies between rehabilitation and industrial exoskeletons. While the goal of the former is to help the user recover damaged/injured motor functions to perform basic and/or daily tasks (e.g., walking), the latter is to assist with more diverse and complex tasks (e.g., load carriage, lifting). Second, the ankle and hip exoskeletons from earlier studies are typically underactuated and often used for one specific body joint, while an industrial powered exoskeleton can provide much greater torques over multiple body joints (e.g., the Sarcos industrial whole-body powered exoskeleton). Such differences in the magnitude of mechanical assistance/support may alter the rate at which a user adapts to the exoskeleton. Kao et al. (2010) reported that users took a longer time to reach a steady state (i.e., adapt) in lower limb joint dynamics when walking with an exoskeleton with greater strength augmentation. Third, in the presence of external assistance, human neuromuscular strategies can vary across different joints due to differential contributions to net mechanical work (Farris and Sawicki, 2012; Neptune et al., 2008). Hence, operating multi-joint exoskeletons, with more degrees-of-freedom and complex control systems, can be more difficult for users (Shen et al., 2019) and will likely require user adaptation periods that are distinct from those observed for single-joint rehabilitation exoskeletons.

The purpose of this study was to explore how novice users alter their motor strategies to operate a whole-body powered exoskeleton prototype (Guardian® XO® 2019 prototype) during gait. We focused on gait performance because it is a fundamental activity for ambulatory tasks in various workplace settings. Our primary hypothesis was that there would be initial differences in gait patterns and muscle activities between novices and experienced users, but these differences would decrease over time (multiple sessions of whole-body powered exoskeleton use) and that novices would exhibit gait patterns similar to those of experienced users when using the exoskeleton within the four gait sessions (one familiarization session and three gait sessions). Four gait sessions were chosen based on earlier studies of adaptation to exoskeleton use during gait (Galle et al., 2013; Gordon and Ferris, 2007; Jacobs et al., 2018; Kao and Ferris, 2009; Panizzolo et al., 2019), which showed that able-bodied users adapted to powered ankle exoskeletons within three sessions (each session lasting less than an hour).

As there is no commercially available whole-body powered exoskeleton at present, such results can provide an important understanding of motor adaptations and learnability of a whole-body powered exoskeleton in an early design stage, which would be particularly valuable for enhancing future designs and developing effective training protocols for whole-body powered exoskeleton use.

2. Methods

2.1. Participants

Eleven healthy (6 novices and 5 experienced users) male participants completed the study. Only male participants were recruited for the current study to meet the anthropometric requirements of the whole-body powered exoskeleton. The exoskeleton was configured only to accommodate individuals 6 feet (1.82 m) tall, with a small tolerance of 0.1 ft (0.03 m) to ensure proper contacts between the user body and control interfaces (i.e., load cells) located at hands, feet, torso, and pelvis of the exoskeleton. Prior to any data collection, informed consent was obtained from each participant following procedures approved by Virginia Tech Institutional Review Board. Respective mean (SD) stature, body mass, and age were 1.8 (0.04) m, 84.4 (6.8) kg, and 36.8 (15.4) years for novice participants; and 1.8 (0.03) m, 83.9 (8.2) kg, and 31.2 (7.8) years for experienced participants. Novice participants had no experience operating the whole-body powered exoskeleton prior to data collection, while the experienced participants had extensive experience in testing and operating the whole-body powered exoskeleton throughout its developmental phases. The experienced participants had been using the exoskeleton for a period of > 3 months, and their proficiency was confirmed by the investigators and engineers from Sarcos in terms of maneuvering and operational skills. No participants had any self-reported musculoskeletal injuries or disorders in the last 12 months.

2.2. Experimental protocol

We used an early prototype version of the Guardian® XO® (EXO for brevity) developed by Sarcos Robotics, which was specifically designed for occupational applications (see Fig. A1 in the Appendix for a detailed description). Novices completed four gait sessions with the EXO and one without it (no-EXO). The first session (~1.5 h) was for familiarization and EXO parameter tuning. During this familiarization session, each participant was given training on basic EXO operations, including how to don/doff the system, along with safety protocols and fitting. When fitting the EXO, participants were asked to step into EXO footplates and then fasten an adjustable harness, including shoulder and chest straps, hip belts, and waist belts to securely connect their bodies to the EXO (see Fig. A1 in the Appendix). They were then taken through a graded protocol, in which they first operated only the upper arm with the EXO to perform a series of movements and lifts, and then walked back and forth on a level gait track several times (with and without loads). These tasks were repeated until participants felt comfortable and confident using the EXO. Tunable control parameters of the EXO (e.g., actuation gains, payload, and gravity compensation) were then adjusted as the participants completed several gait trials along a linear 10 m gait track. Participants were also trained to bend down to pick up loads and maneuver these loads to different target locations (ranging from ankle to shoulder level) to experience a full range of motion at major body joints while in the EXO.

Following this familiarization session, three subsequent gait sessions (S1-S3), each lasting about 4 hours, were completed. In each of the three gait sessions, no further specific training was provided, and data were collected when participants walked along the linear gait track at their preferred gait speed four times (i.e., four trials). In each session, novices also performed various industrial tasks such as lifting and load carriage, although only an analysis of the gait trials is presented here. All three gait sessions for the novices were completed within a four-day experimental period to minimize potential fatigue development or any long-term loss in adaptation, and the sessions were at least two hours apart. Novices performed one no-EXO condition during either session 1 or 3. Experienced users completed one gait session with and without the EXO on the same day.

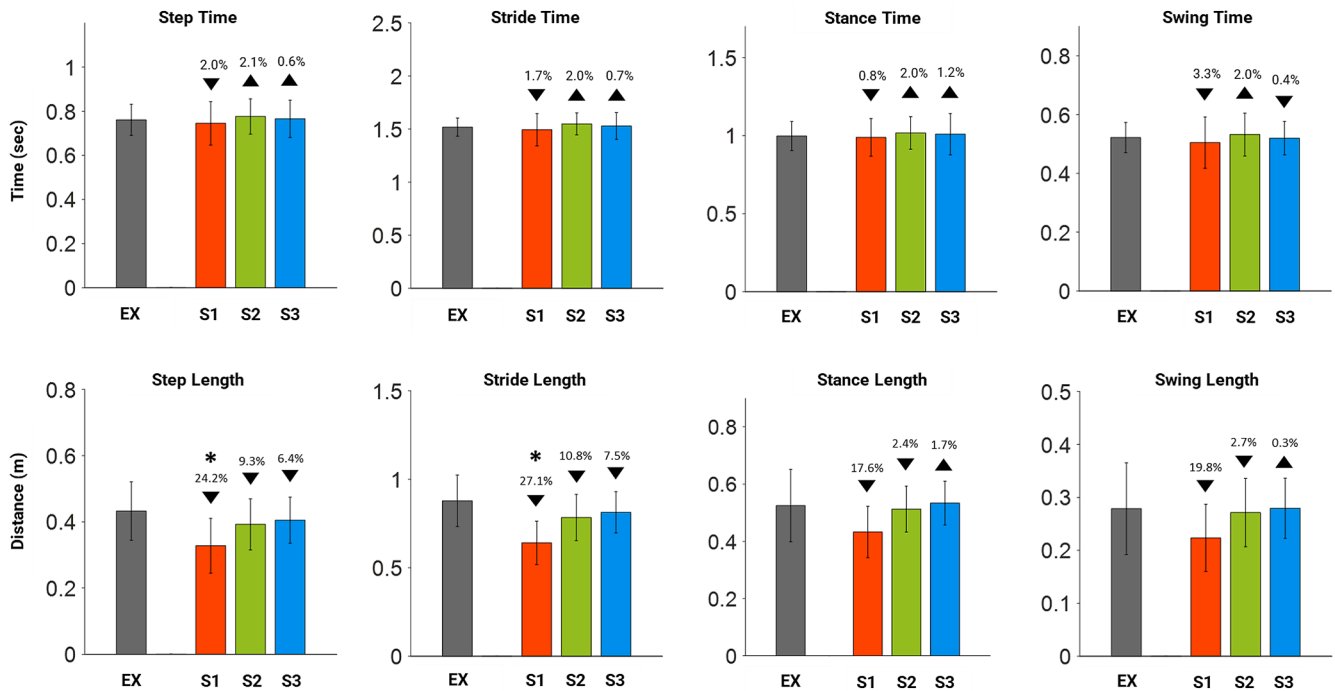


Fig. 1. Spatiotemporal gait measures consisting of four temporal measures (top) and four spatial measures (bottom) monitored during each gait session. Each bar represents the mean value across participants in each session. Error bars represent standard deviations. The upward and downward arrows indicate percentage changes in the mean spatiotemporal measures of novices from each session (S1-S3) compared to the experienced users (EX). The symbol * indicates a significant paired difference between the corresponding novice session and the experienced user session.

2.3. Instrumentation and data processing

Whole-body kinematics were measured at 60 Hz using an inertial motion capture system (MTW Awinda, Xsens Technologies B.V., Enschede, The Netherlands) that consists of 17 inertial measurement units (IMUs) placed on major body segments. Whole body joint kinematics were extracted using MVN Animate (Xsens, version 2019.2.1). The Xsens system uses the standard rotation sequence recommended by ISB (ZXY) to obtain joint kinematics and 3D coordinates of anatomical landmarks (Wu et al., 2005).

For the current analyses, we extracted four joint angles in the sagittal plane (i.e., pelvis, hip, knee, and ankle) from the right leg. Pelvic tilt was computed globally as the angle between the pelvis segment and the vertical axis perpendicular to the ground; hip joint angle was computed as the angle between the pelvis and thigh segments; knee joint angle was between the thigh (femur) and shank (tibia) segments; and ankle joint angle was between the shank and foot (calcaneus) segments.

Muscle activity in the right leg was monitored at 1.5 kHz using a telemetered surface electromyographic (EMG) system (Ultium, Noraxon, AZ, USA). For novices, muscle activity was only measured during sessions 1 and 3, mainly because participants had limited availability for data collection and the instrumentation required rather a long preparation time. Initial skin preparation was performed, involving shaving and cleaning with alcohol. Pairs of pre-gelled, bipolar, Ag/AgCl electrodes with a 2.5 cm inter-electrode spacing were placed unilaterally (right-side) over four accessible, lower extremity muscle groups following procedures described earlier (Cram et al., 1998): vastus lateralis (VL), biceps femoris (BF), anterior tibialis (TA), and medial gastrocnemius (MG). Participants then performed maximum voluntary isometric contractions (MVICs) for each muscle group for EMG normalization. For the thoracic and lumbar muscles, participants stood with their trunk flexed to $\sim 20^\circ$, with their feet slightly separated, and performed maximal trunk extension while their pelvis and legs were secured to a rigid fixture (Jia et al., 2011). To perform MVICs for the leg, participants sat on a chair with their knee joint angle maintained at $\sim$

90° , and they performed knee and ankle flexion and extension against manual resistance (Babault et al., 2001). Upon completing MVICs, a minimum of 5 minutes of rest was provided. Raw EMG signals were band-pass filtered (20–450 Hz, 4th-order Butterworth, bidirectional), and root-mean-square (RMS) amplitudes were obtained with a 300 ms moving window to create linear envelopes. For each gait trial, EMG linear envelopes for each of the four muscle groups were normalized to the corresponding peak values obtained during the MVICs to achieve normalized EMG (NEMG) envelopes.

2.4. Outcome measures

All analyses were performed based on gait cycles obtained from the gait sessions. A gait cycle was defined from the sequential right heel strikes identified from the IMU system and was visually confirmed using MVN Animate software. Once all gait cycles were identified, spatiotemporal dependent measures were extracted for each of the EXO gait trials and no-EXO gait trials. Spatiotemporal gait measures were calculated following earlier gait studies (Gutierrez et al., 2005; Vilensky et al., 1981). Specifically, step lengths were determined as the absolute distance between the consecutive left and right heel strikes, and stride lengths as the distance between consecutive right heel strikes. Accordingly, step and stride times were measured as the times it took participants to perform each step and stride. Stance phases were determined as the proportion of the stride where the right foot was making contact with the ground, and the swing phases were when the right foot was not making ground contact (toe-off to heel strike of the right foot). Gait speed was computed by dividing stride length by stride time. Then, each gait cycle was resampled to 100 normalized time points (i.e., 0–100% gait cycle). From the normalized gait cycles, lower-limb joint angles (pelvis tilt, hip, knee, and ankle) and muscle activities (RVL, RBF, RTA, and RMG) were extracted. To understand how the EXO was operated, we also extracted lower-limb EXO joint torques (hip, knee, and ankle) in the sagittal plane and human-EXO interaction forces measured from the 6-DOF load cells at the EXO pelvis and feet.

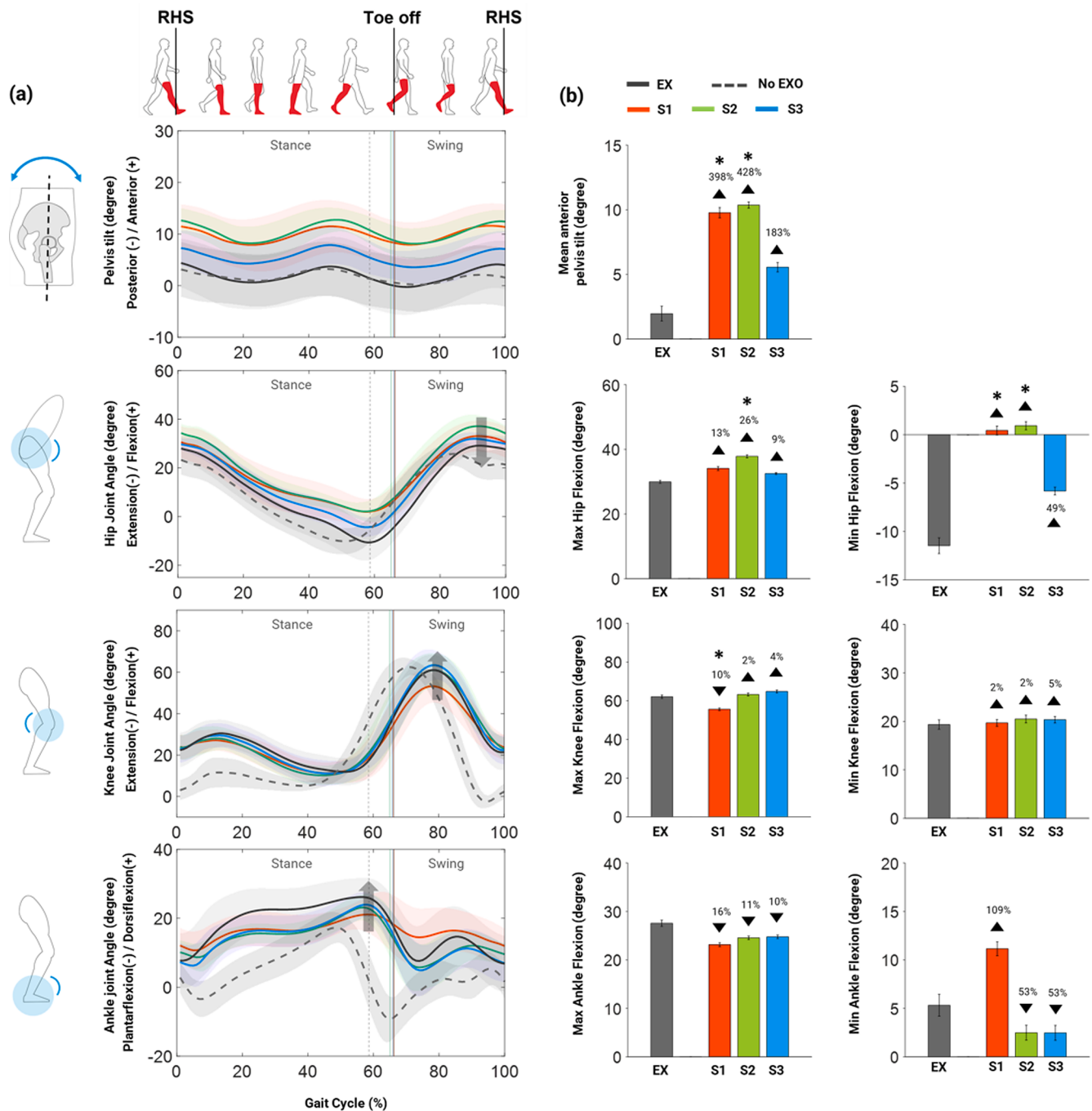


Fig. 2. (a) Pelvis, hip, knee, and ankle joint angles of the right lower limb during gait. Each gait cycle is defined as sequential right-heel strikes (RHS). Solid lines represent the mean joint angles of novice session 1 (red), 2 (green), 3 (blue), and the experienced users (black). The dashed black line represents the mean joint angles of the no-EXO session of all participants. Vertical lines represent the timing of the toe-off of each gait session. The colored shaded regions indicate ± 1 standard deviation (SD) for each corresponding gait session. (b) Mean pelvic tilt (first row) and max and min for the hip (second row), knee (third row), and ankle (fourth row) joint angles. Each bar represents the mean value across participants in each session, and error bars represent standard errors. Upward and downward arrows indicate percentage changes in mean joint angles of novices from each session (S1-S3) compared to the experienced users (EX). The symbol * indicates a significant paired difference between the corresponding novice session and the experienced user session. Time to peak joint angles for the hip, knee, and ankle were log-transformed to meet parametric model assumptions.

Means and standard deviations of each dependent measure at each normalized time point were calculated as representative values for illustrating gait performance measures (i.e., joint angles, muscle activities, EXO joint torques, and EXO foot and pelvis contact forces). Summary outcome measures were computed over the gait cycle, as described below. Spatiotemporal gait measures included step/stride and swing/stance times and lengths. For joint kinematics, peak and time-to-peak

values for sagittal plane joint angles (hip, knee, and ankle) were computed. Peak hip flexion and extension were computed from the swing and stance phases, respectively, and peak knee flexion and extension were both computed from the swing phase in accordance with when these events occur during typical gait (i.e., when not powered with an EXO). However, peak ankle plantar flexions were computed during 40–80% of the gait cycle (i.e., including the stance-swing transition),

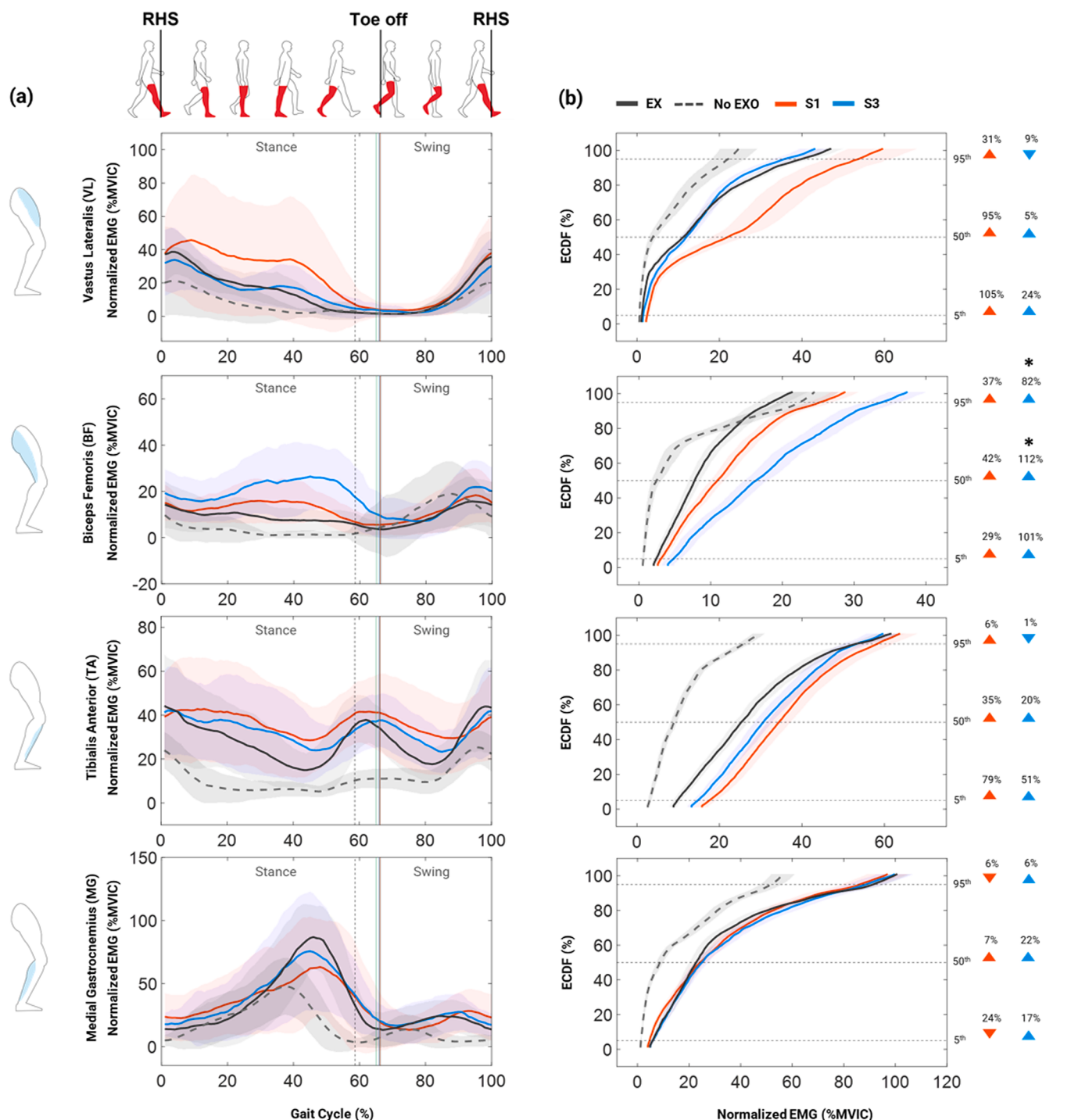


Fig. 3. (a) Muscle activities of four lower-limb muscle groups (VL, BF, TA, MG) during gait. Each gait cycle is defined as sequential right-heel strikes (RHS). Solid lines represent the mean NEMGs of novice session 1 (red), 3 (blue), and the experienced users (black). The dashed black line represents the mean NEMGs from the no-EXO session of all participants. Vertical lines represent the timing of the toe-off of each gait session. The colored shaded regions indicate $\pm$ standard deviation (SD) for each corresponding gait session. (b) The empirical cumulative distribution function (ECDF) of estimated muscle activity of the VL (first row), BF (second row), TA (third row), and MG (fourth row). Solid lines represent the mean muscle activity of novice session 1 (red), 3 (blue), and the experienced users (black). The dashed black line represents the mean muscle activity of the no-EXO session of all participants. Colored regions indicate ± 2 standard error for each corresponding lifting/lowering session. Upward and downward arrows indicate percentage changes in the mean muscle activities of novices from each session (S1-S3) compared to the experienced users (EX). The symbol * indicates a significant paired difference between the corresponding novice session and the experienced user session. The 5th, 50th, and 95th percentile values of the VL and BF muscle activity and the 5th percentile value of the TA and MG were log-transformed to meet parametric model assumptions.

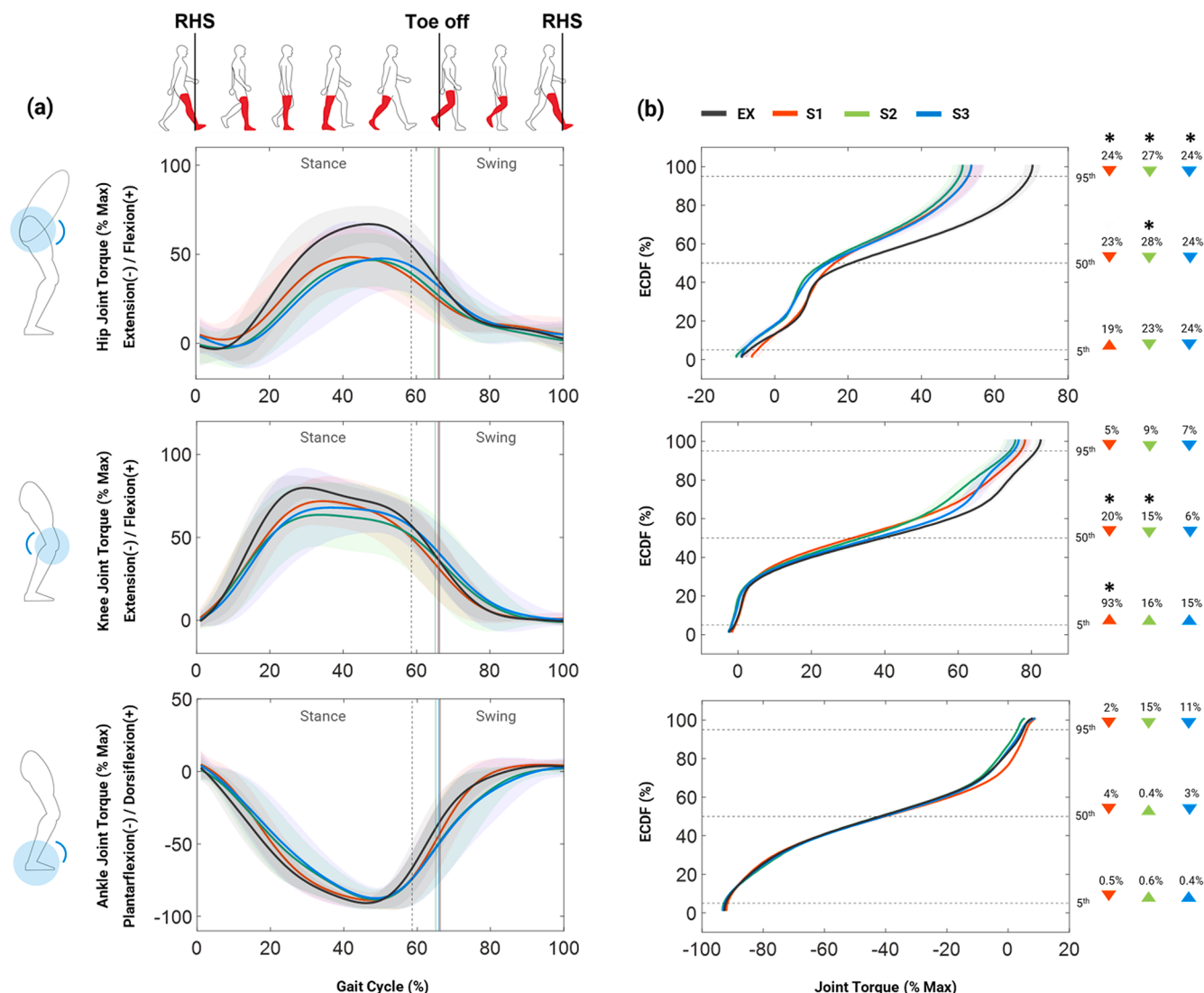


Fig. 4. (a) EXO joint torques of the right lower limb (hip, knee, and ankle) monitored during gait. Each gait cycle is defined as sequential right-heel strikes (RHS). Solid lines represent the mean joint angles of novice session 1 (red), 2 (green), 3 (blue), and the experienced users (black). Vertical lines represent the timing of the toe-off of each gait session. The colored shaded regions indicate ± 1 standard deviation (SD) for each corresponding gait session. (b) The empirical cumulative distribution function (ECDF) of estimated EXO joint torques of the hip (first row), knee (second row), and ankle (third row). Solid lines represent the mean muscle activity of novice session 1 (red), 3 (blue), and the experienced users (black). The dashed black line represents the mean muscle activity of the no-EXO session of all participants. Colored regions indicate ± 2 standard error for each corresponding lifting/lowering session. Upward and downward arrows indicate percentage changes in the mean EXO joint torques of novices from each session (S1-S3) compared to the experienced users (EX). The symbol * indicates a significant paired difference between the corresponding novice session and the experienced user session. The 95th percentile value of the EXO knee joint torque and the 5th, 50th, and 95th percentile values of the EXO ankle joint torque were log-transformed to meet parametric model assumptions.

since peak plantar flexion appeared to be somewhat delayed when walking in the EXO compared to the baseline (no-EXO). For pelvic tilt, instead of peak values, a mean value was computed over the gait cycle in accordance with prior studies (Lewis and Sahrman, 2015; Mendiguchia et al., 2021).

For muscle activity, percentiles (5th, 50th, 95th) of the empirical cumulative distribution function (ECDF) were estimated from the NEMG of each muscle. Similarly, the 5th, 50th, and 95th percentiles of the ECDF of EXO joint torques were estimated to understand how each participant utilized the EXO while walking. For describing the human-EXO interactions during gait, peak values of EXO foot and pelvis load cells were computed, both at heel-strike and toe-off. Data from at least two gait trials in each experimental session were included for analysis.

2.5. Statistical analysis

Separate linear mixed models were used for each outcome measure, with the session as a fixed factor and the subject as random effects, to compare each of the novice EXO sessions with the experienced user EXO session. The unstructured covariance type was used, and the restricted maximum likelihood (REML) estimation method was chosen. All data were examined for normality and homogeneity using the Shapiro-Wilk Test. Where residuals exhibited substantial deviations from the normal distribution, appropriate data transformations were performed to meet parametric model assumptions (see Tables A1-A4 in the Appendix for details). All analyses were performed using JMP Pro 15.0 (SAS Institute Inc., Cary, NC), and statistical significance was determined when $p < 0.05$.

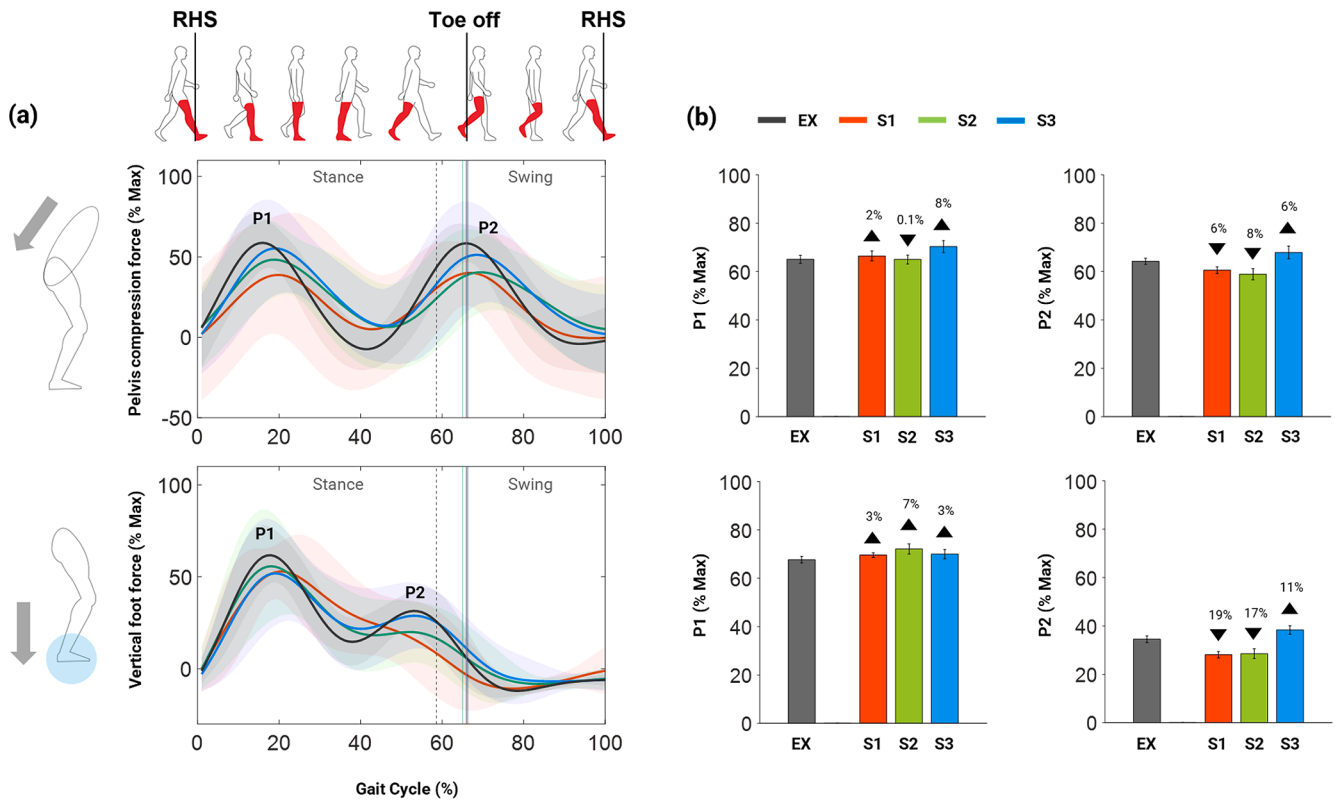


Fig. 5. (a) EXO load cell values of the pelvis and vertical right foot monitored during gait (first column). Each gait cycle is defined as sequential right-heel strikes (RHS). Solid lines represent the mean joint angles of novice session 1 (red), 2 (green), 3 (blue), and the experienced users (black). Vertical lines represent the timing of the toe-off of each gait session. The colored shaded regions indicate ± 1 standard deviation (SD) for each corresponding gait session. (b) Peak EXO load cell values of the pelvis and vertical right foot during heel strike (P1) and toe-off (P2). Each bar represents the mean value across participants in each session, and error bars represent standard errors. Upward and downward arrows indicate percentage changes in the mean load cell values of novices from each session (S1-S3) compared to the experienced users (EX). The symbol * indicates a significant paired difference between the corresponding novice session and the experienced user session. Time to peak load cell values of the pelvis and vertical right foot during P1 were square transformed, and during P2, were log transformed to meet parametric model assumptions.

3. Results

3.1. Spatiotemporal gait measures

For all temporal measures (step, stride, stance, and swing times), there were relatively small differences between novices and experienced users ($\sim 3\%$) across all three gait sessions (Fig. 1). Larger differences between novices and experienced users were observed in the spatial measures ($\sim 27\%$), and the magnitude of these differences decreased over subsequent sessions. Specifically, the novices had significantly shorter step and stride lengths in their first session [$\sim 27\%$ (~ 0.24 m) lower], and these differences became smaller in later sessions. There were no significant differences between novices and experts in other spatiotemporal measures.

3.2. Joint kinematics

Initial differences in joint angles between the novices and the experienced users generally decreased as novices spent more time in the EXO, but such changes over sessions differed across joints (Fig. 2). Specifically, novices walked with significantly greater anterior pelvic tilt throughout the entire gait cycle in sessions 1 and 2. Although they altered their pelvic tilt to be more consistent with experienced users in session 3 (with no significant difference in this session), there was still a roughly 180% difference ($\sim 5.6^\circ$ for the novices and $\sim 1.9^\circ$ for the experienced users). Hip joint angles between novices and experienced users differed significantly during most phases of the gait cycles in all gait sessions (Fig. 2). In particular, novices utilized significantly higher

peak hip flexions and lower peak hip extension during all EXO gait sessions. On the contrary, knee joint kinematics were comparable between novices and experienced users throughout all sessions. A significant difference in mean peak knee flexion between novices and experienced users only occurred in session 1 (lower), the magnitude of which was up to $\sim 10\%$ ($\sim 6.5^\circ$) on average. For the ankle joint, novices had less dorsiflexion through all gait sessions (between 10% and 16%; 2.8° - 4.4°); however, these differences were not statistically significant. In summary, significant differences occurred in anterior pelvic tilt during sessions 1 and 2, peak hip flexion during session 2, peak hip extension during sessions 1 and 2, and peak knee flexion during session 1.

3.3. Muscle activity

Alterations in motor strategies were less pronounced in leg NEMG profiles (Fig. 3). While novices utilized higher VL muscle activity during the stance phase in session 1, the difference between novices and experienced users was substantially reduced by session 3 (a $\sim 31\%$ difference in the 95th percentile VL muscle activity in session 1 decreased to a $\sim 9\%$ difference in session 3). However, the differences in the 5th, 50th, and 95th percentile VL muscle activity were not statistically significant. Likewise, no significant differences between novices and experienced users were observed for TA or MG. For the TA, however, the time series and ECDF plots indicated novices had 20–35% higher median (50th percentile) muscle activity. For the MG, novices and experienced users had nearly identical muscle activity patterns in both gait sessions. On the other hand, novices exhibited notably higher

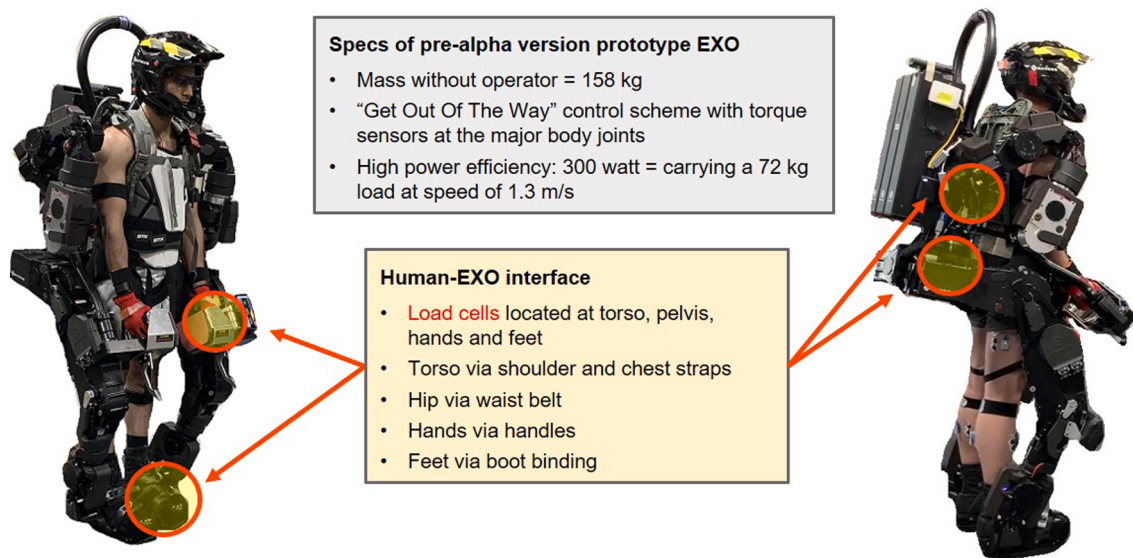


Fig. A1. Pre-alpha prototype of the occupational whole-body powered exoskeleton (EXO) tested (Guardian® XO®, Sarcos Robotics, <https://www.sarcos.com>). The red circled areas denote the human-EXO load cell (6-DOF force-moment sensor) interfaces where the EXO measures human-EXO interaction forces. The EXO has a mass of 158 kg and includes 18 active DOFs spanning the shoulders (flexion/extension, abduction/adduction, and internal/external rotation), elbows (flexion/extension), trunk (axial rotation and lateral bending), hips (flexion/extension, abduction/adduction, and axial rotation), and knees (flexion/extension). At the time of assessment, the EXO was still in the development stage, and the calf and ankle joints were not actuated. The EXO uses a patented “Get-Out-Of-The-Way” control scheme with torque sensors at the major body joints that allow the EXO to follow the human movement and amplify human joint torques (Jacobsen et al., 2014). With this technology, users can be assisted to freely lift and handle loads up to 90 kg. To understand user movement intent, user input is obtained from embedded 6-DOF force-moment load cells located at the hands, feet, torso, and pelvis locations of the EXO. The EXO also has several tunable parameters, including the virtual center of mass, gravity compensation, and actuation gains (magnitude of torque amplification).

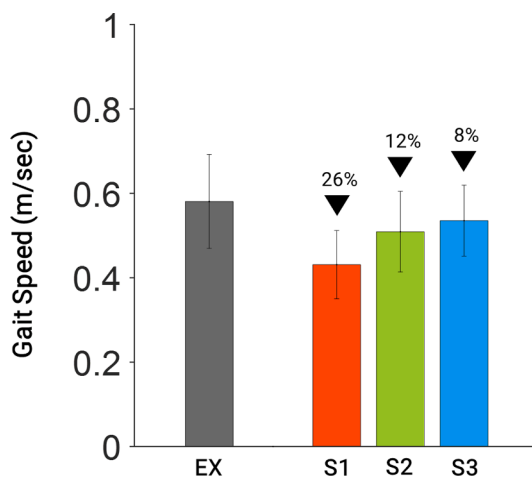


Fig. A2. Gait speed monitored during each session. Each bar represents the mean value across participants in each session, and the error bars represent standard deviations. Upward and downward arrows indicate percentage changes in the mean spatiotemporal measures of novices from each session (S1-S3) compared to the experienced users (EX).

overall BF activity (~42% in session 1 and ~112% in session 3). However, statistical significance was only found in 50th and 95th percentile BF activities in session 3 (~112% and ~82%, respectively).

3.4. EXO joint torques generated

In terms of EXO torques, the most notable result was that novices utilized significantly lower EXO hip flexion torques (Fig. 4). In particular, the 95th percentile EXO hip flexion torque was ~27% (~19 Nm) lower for novices in all three sessions. Novices also exhibited ~28% (~6.5 Nm) lower 50th percentile EXO hip flexion torques across all

sessions, but the difference was only significant in session 2. Similarly, median (50th percentile) EXO knee flexion torques for novices were lower (~20%; ~8 Nm) in all three sessions. However, the magnitude of this difference decreased in later sessions, and no significant difference was found in session 3. Based on time-series plots, differences in hip and knee flexion torques were more evident during the stance phase. No clear differences were found in ankle joint torque profiles between novices and experienced users during EXO use (<5% differences in the 95th percentile torque values). In summary, significant differences were found in 95th percentile values of the hip flexion torque during all three sessions, while 50th percentile values were only significant during session 2. The 50th percentile values of the knee flexion torque showed significant differences in sessions 1 and 2, but the 5th percentile value was only significant during session 1.

3.5. Human-EXO interaction force

Time-series plots of pelvis compression and foot interaction force profiles (Fig. 5) revealed that novices and experienced users generally had similar profiles across the gait cycle. Indeed, there were no significant differences between novices and experienced users for mean values of peak pelvis compression and foot interaction forces during either heel strike (P1) or toe-off (P2) in any of the sessions. During sessions 1 and 2, however, novices exhibited a substantial delay in peak foot interaction force during toe-off (P2). This delay, though, was reduced by session 3 (~11% in session 1 to ~6% in session 3).

4. Discussion

Our findings show that gait patterns between novices and experienced users differed most substantially in the first gait session but that such differences became smaller in the later sessions. These results suggest that the novices adapted during continued EXO use. However, the rates of adaptation differed across the various dependent measures examined: while spatiotemporal gait measures showed the fastest rate of

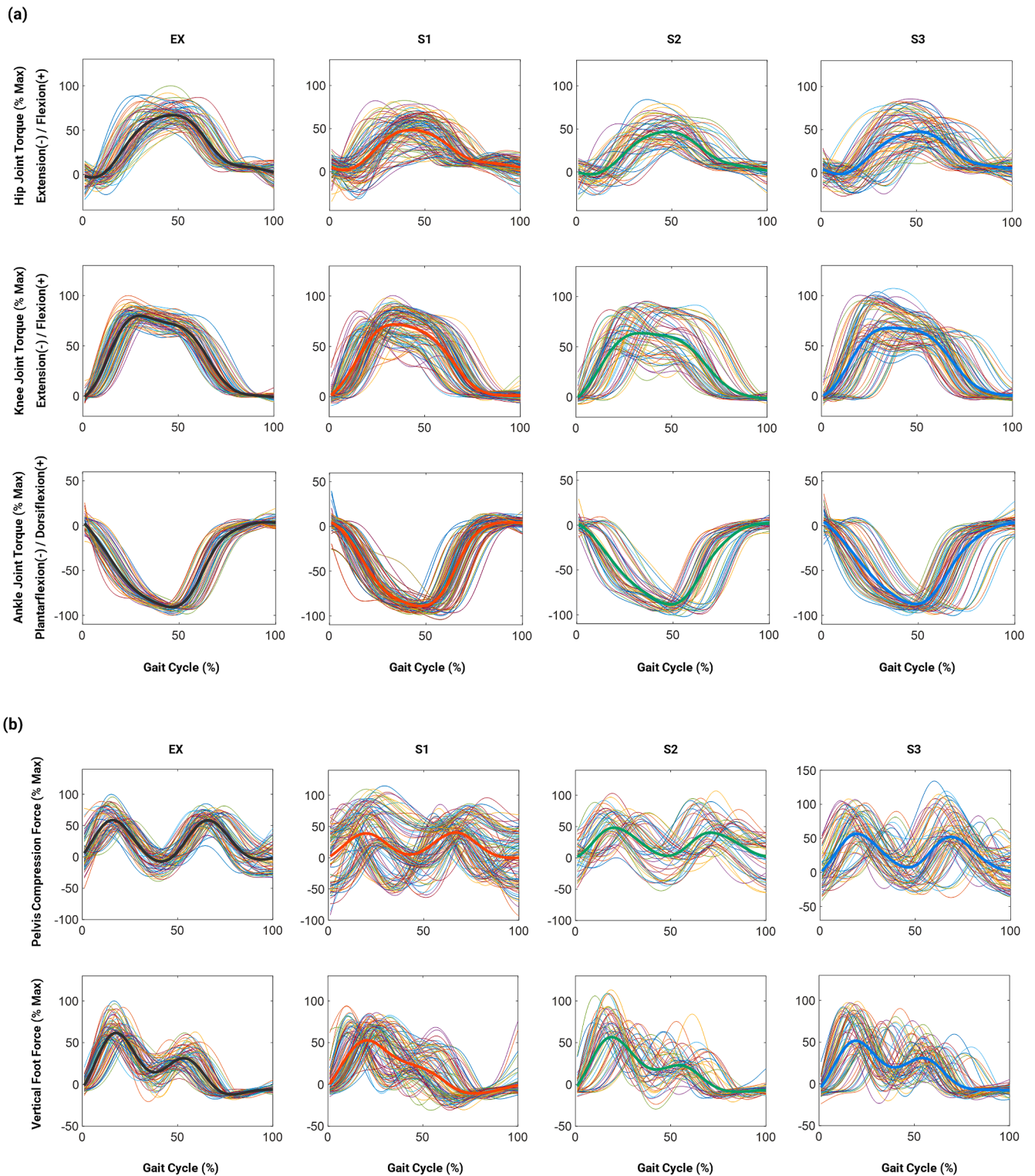


Fig. A3. (a) Individual EXO joint torques data of the right lower limb (hip, knee, and ankle) monitored during gait for the experience users (first column from the left side) and novice session 1 (second column), 2 (third column), and 3 (fourth column). (b) Individual EXO load cell data of the pelvis and vertical right foot monitored during gait for the experience users (first column from the left side), and novice session 1 (second column), 2 (third column), and 3 (fourth column). Each time-series plot shows the individual stride of the gait session. Solid lines represent mean EXO joint torques and EXO load cell values of the novice session 1 (red), 3 (blue), and the experienced users (black).

adaptation, joint kinematics, and EXO joint torque profiles showed slower rates of change. Novices still had greater pelvic tilt and hip extension by session 3.

4.1. Spatiotemporal measures

Motor adaptations were most pronounced for the gait spatiotemporal measures, and especially the spatial measures of step and stride lengths (see Fig. 1). While novices and experienced users employed similar step

Table A1

Descriptive summaries of mean (standard deviation) peak (min and max) joint angles and time to these peak joint angles (% gait cycle) measured from the sagittal plane. For novices, [p-values] corresponding to pairwise comparisons of each novice session with the experienced user session are presented. Values with bold font indicate a difference between novices and experienced users that was statistically significant ($p < 0.05$).

Joint angles (degree)		Novices						Experienced users	
Joints	Data transform	Session 1		Session 2		Session 3		Mean	Min
Pelvic tilt	–	Mean 9.78 (4.2) [0.0041]		Mean 10.36 (2.2) [0.0025]		Mean 5.56 (3.2) [0.1646]		1.96 (5.0)	
Hip	–	Max 33.97 (6.3) [0.0633]	Min 0.41 (4.9) [0.0024]	Max 37.84 (4.3) [0.0047]	Min 0.93 (3.8) [0.0020]	Max 32.52 (2.5) [0.5518]	Min –5.82 (3.5) [0.0980]	29.96 (3.9)	–11.47 (7.2)
Knee	–	55.70 (7.4) [0.0469]	19.65 (7.4) [0.9860]	63.18 (6.8) [0.8362]	20.48 (7.2) [0.9822]	64.74 (6.4) [0.8647]	20.33 (6.0) [0.8517]	62.05 (7.3)	19.33 (8.4)
Ankle	–	23.16 (4.2) [0.0803]	11.15 (7.7) [0.2592]	24.56 (3.2) [0.2034]	2.49 (6.9) [0.4902]	24.77 (3.2) [0.1870]	2.48 (6.7) [0.6072]	27.57 (5.6)	5.33 (10.0)
Time to peak		Max	Min	Max	Min	Max	Min	Max	Min
Hip	Log	91.26 (4.4) [0.4364]	57.31 (4.4) [0.6253]	91.74 (3.7) [0.6384]	57.05 (3.9) [0.6407]	91.03 (3.8) [0.6070]	57.56 (3.4) [0.8970]	92.83 (4.2)	58.4 (2.7)
Knee	Log	77.47 (3.8) [0.6132]	80.73 (18.2) [0.1571]	77.78 (3.8) [0.7331]	88.19 (17.2) [0.9013]	78.27 (2.6) [0.3493]	91.31 (14.9) [0.7571]	77.91 (2.4)	88.90 (16.0)
Ankle	Sqrt	61.01 (6.5) [0.1171]	64.98 (14.6) [0.0221]	58.28 (4.4) [0.5134]	72.42 (6.06) [0.9327]	58.10 (3.9) [0.3388]	73.12 (6.2) [0.5839]	56.83 (7.7)	73.04 (5.2)

Table A2

Descriptive summaries of the mean (standard deviation) percentile values (5th, 50th, and 95th) of normalized muscle activity (NEMG, units = %MVIC). For novices, [p-values] corresponding to pairwise comparisons of each novice session with the experienced user session are presented. Values with bold font indicate a difference between novices and experienced users that was statistically significant ($p < 0.05$).

Muscle group	Percentile	Data transform	Novices		Experienced users
			Session 1	Session 3	
Vastus Lateralis (VL)	5th	Log	2.44 (3.1) [0.7478]	1.51 (1.1) [0.4871]	1.26 (0.6)
	50th	Log	22.10 (20.6) [0.4676]	12.3 (6.4) [0.5947]	11.88 (5.1)
	95th	Log	53.45 (40.1) [0.9199]	38.79 (15.5) [0.8674]	41.95 (13.5)
Biceps Femoris (BF)	5th	Log	3.39 (2.5) [0.5606]	5.56 (5.9) [0.1743]	2.57 (2.0)
	50th	Log	11.29 (5.0) [0.2066]	17.36 (9.4) [0.0310]	7.93 (4.2)
	95th	Log	26.52 (8.8) [0.1605]	36.47 (15.0) [0.0246]	19.14 (10.8)
Tibialis Anterior (TA)	5th	Log	17.13 (9.6) [0.0802]	13.85 (7.4) [0.1174]	10.04 (5.0)
	50th	–	33.16 (15.4) [0.1261]	28.23 (14.1) [0.2337]	25.55 (8.6)
	95th	–	57.18 (21.4) [0.7082]	52.42 (18.9) [0.7763]	56.09 (15.6)
Medial Gastrocnemius (MG)	5th	Log	4.95 (2.5) [0.7084]	6.55 (4.5) [0.6729]	6.37 (5.3)
	50th	–	25.42 (12.5) [0.7549]	25.82 (12.7) [0.6474]	23.39 (13.3)
	95th	–	89.11 (37.8) [0.4538]	91.39 (36.2) [0.2418]	93.95 (24.7)

and stride times in all three gait sessions, novices took longer steps with greater speed in each subsequent gait session. The significant differences in novice gait (i.e., shorter step and stride lengths) were only evident during session 1. Although there was a difference in the magnitude of gait speed (novices were ~ 24% slower than experienced users in session 1 and ~ 8% slower in session 3; Fig. A2 in Appendix), there were no significant differences. No significant or substantial baseline (no-EXO condition) differences were found between novices and experienced users, which suggests that potential confounding effects of group differences in gait speed were minimal.

The shorter step lengths and time (i.e., slower gait speed) used by novices in the earlier sessions may be explained by their need to walk more slowly to preserve gait stability. Walking with a slower gait speed (England and Granata, 2007) or a shorter step length (Hak et al., 2012)

has been shown to increase gait stability. Using a slower gait speed in exoskeleton-assisted conditions, and the potential reason for this being preservation of gait stability, has also been reported previously (e.g., Haufe et al., 2021; Kim et al., 2021).

Our finding of reduced spatial measures (step, stride, swing, and stance length) while walking in the EXO is not consistent with some recent studies on passive hip exoskeletons (Feodoroff and Blümer, 2022; Panizzolo et al., 2021; Pircoveanu et al., 2022). Participants in these earlier studies exhibited enhanced spatiotemporal measures (i.e., increased step length) or no differences between EXO and baseline conditions. These differences in spatial measures may be due to differences in exoskeleton form and actuation type (i.e., powered vs. passive), magnitudes of torque assistance provided, number of joints actuated (i.e., multi vs. single jointed), and/or design purposes (strength-

Table A3

Descriptive summaries of the mean (standard deviation) percentile values (5th, 50th, and 95th) of joint torques for the EXO. All EXO joint torque values are normalized to the absolute peak value of experienced users. For novices, [p-values] corresponding to pairwise comparisons of each novice session with the experienced user session are presented. Values with bold font indicate a difference between novices and experienced users that was statistically significant ($p < 0.05$).

Joints	Percentile	Data transform	Novices			Experienced users
			Session 1	Session 2	Session 3	
Hip	5th	–	3.25 (2.5) [0.1547]	2.14 (1.5) [0.4124]	2.14 (1.3) [0.1430]	2.78 (1.6)
	50th	–	17.88 (5.3) [0.1008]	16.78 (5.8) [0.0366]	18.13 (7.6) [0.1179]	23.32 (7.1)
	95th	–	52.45 (15.5) [0.0166]	50.72 (13.9) [0.0132]	53.12 (18.2) [0.0411]	69.78 (10.6)
Knee	5th	–	1.13 (1.1) [0.0174]	0.68 (0.4) [0.7728]	0.67 (0.5) [0.8621]	0.58 (0.4)
	50th	–	34.22 (7.6) [0.0070]	36.19 (9.7) [0.0146]	39.44 (8.6) [0.5525]	42.23 (5.9)
	95th	Log	77.52 (9.9) [0.6154]	74.71 (16.4) [0.0966]	75.01 (16.2) [0.4387]	81.85 (6.4)
Ankle	5th	Log	1.57 (0.9) [0.6872]	0.68 (0.6) [0.7055]	0.67 (0.5) [0.1639]	1.61 (0.8)
	50th	Log	36.38 (8.6) [0.1013]	38.77 (8.0) [0.7693]	38.14 (6.2) [0.3121]	38.74 (5.7)
	95th	Log	91.30 (4.3) [0.6199]	92.31 (4.2) [0.8631]	92.34 (3.5) [0.7886]	91.60 (2.9)

Table A4

Descriptive summaries of the mean (standard deviation) peak pelvis and vertical right foot load cell values and time to these peak load cell values during heel strike (P1) and toe-off (P2). All EXO load cell values are normalized to the corresponding absolute peak value of experienced users. For novices, [p-values] corresponding to pairwise comparisons of each novice session with the experienced user session are presented. Values with bold font indicate a difference between novices and experienced users that was statistically significant ($p < 0.05$).

Load cell forces	Peaks	Data transform	Novices			Experienced users
			Session 1	Session 2	Session 3	
Pelvis compression force	P1	–	66.45 (21.0) [0.7814]	64.98 (14.2) [0.6413]	70.33 (21.6) [0.3361]	65.08 (14.6)
	P2	–	60.56 (14.4) [0.4761]	58.92 (18.3) [0.2353]	67.91 (23.1) [0.5059]	64.24 (11.1)
Vertical foot force	P1	–	69.60 (10.0) [0.7962]	72.11 (16.7) [0.8254]	70.00 (17.0) [0.9381]	67.65 (12.1)
	P2	–	28.10 (13.3) [0.1192]	28.49 (15.9) [0.1128]	38.33 (15.1) [0.5010]	34.52 (11.9)
Time to peak Pelvis compression force	P1	Sqrt	17.64 (13.7) [0.2985]	22.02 (10.1) [0.3188]	21.03 (9.3) [0.2499]	16.06 (4.4)
	P2	Log	74.86 (15.5) [0.1118]	71.84 (14.4) [0.3616]	70.13 (8.9) [0.3081]	66.19 (4.6)
Vertical foot force	P1	Sqrt	21.18 (8.0) [0.7601]	20.11 (8.5) [0.9702]	22.52 (9.1) [0.1181]	17.86 (4.0)
	P2	Log	60.36 (7.8) [0.0184]	59.55 (7.7) [0.0076]	57.39 (6.9) [0.3012]	54.59 (4.2)

augmentation vs. gait-assistance). Future research efforts, however, are warranted to assess the factors contributing to differences in spatial measures.

4.2. Joint kinematics

Our first hypothesis, that novices will initially employ significantly different joint kinematics compared to experienced users and that such differences will decrease with EXO use, was supported. While novices demonstrated substantial adaptations in their knee and ankle joint movements over time, differences in pelvic and hip kinematics between novices and experienced users remained, to some extent, even in session 3. Although there were no statistically significant differences between novices and experienced users in pelvic and hip kinematics by session 3, the magnitude of the differences in mean pelvic tilt and peak hip extension was still substantial (~180% and ~49%, respectively).

Novices walked with less hip extension and greater hip flexion (Fig. 2), a difference that may be due to restrictions to ankle motion caused by the steel-toe boots worn by participants (in all participants in

all conditions). The restricted ankle motions likely occurred because the users' feet were secured to the footplates of the EXO since the load cell in the footplate was one main input to EXO control. Also, the EXO version assessed here was a prototype and had only a partially actuated ankle joint, which might have limited the ankle joint motion of the user. Considering that ankle push-off force plays an important role in gait kinematics (JudgeRoy et al., 1996), limited support from the ankle joint likely affected the gait kinematics of participants when walking in the EXO. In fact, Romkes and Schweizer, (2015) similarly reported that walking with an ankle-foot-orthosis, which substantially restricted ankle plantar flexion, induced significantly less hip extension and greater hip flexion. However, despite the same restrictions in ankle motion, experienced users seemed to have learned how to effectively use their hip joints to compensate for the limited ankle range of motion, while novices seemed to have not developed such a technique within the period of the current study.

Another factor that could have contributed to the differences in hip motion between novices and experienced users was their upper body postures while walking in the EXO. In sessions 1 and 2, novices walked

with postures involving significantly more forward flexion of the upper body [$\sim 412\%$ ($\sim 8^\circ$) more compared to experienced users] and less hip extension [$\sim 106\%$ ($\sim 12^\circ$) less compared to experienced users]. Lewis and Sahrmann (2015) reported that walking in a forward flexed posture resulted in up to 20° decrease in hip extension compared to walking in a swayback posture and could be less effective in using their hip joint moments to propel walking forward. We also found earlier that experienced users tend to drive their gait using larger hip joint moments when walking with vs. without the EXO (Kim et al., 2021). Therefore, we believe that experienced users adapted to EXO use by walking with significantly less anterior pelvic tilt, both to compensate for the restricted support from the EXO ankle joints and to use their hip joints more effectively. Although our results on gait spatiotemporal measures may not be directly comparable to earlier passive hip exoskeletons, our findings of increased hip flexion and decreased hip extension during the use of EXO align with recent results reported by Feodoroff and Blümer (2022).

4.3. Muscle activity and EXO joint kinetics

Novices initially had significantly higher levels of muscle activity than experienced users, but these differences mostly reduced over time. In sessions 1 and 3, novices had higher peak (95th percentile) hip extensor/knee flexor (BF) activities during the stance phase (Fig. 3). This higher peak BF activity may be related to novices having more flexed walking postures since walking with flexion significantly increases the need for hip extensor muscle activity (Kluger et al., 2014; Lewis and Sahrmann, 2015). Also, the higher peak BF activity exhibited by novices may be explained by differences in how novices and experienced users utilized the EXO. Specifically, novices had significantly lower peak EXO hip torques during the stance phase (Fig. 4) and yet higher peak BF activity. Although not statistically significant, they also had higher peak VL activity ($\sim 31\%$ in session 1 and $\sim 9\%$ in session 3). Novices exhibiting higher hip flexor and extensor muscle activities suggest that they may have increased their biological joint torque to exert the necessary joint torque for walking in the EXO. Since this was also accompanied by lower EXO hip torques from novices compared to experienced users, this suggests that novices and experienced users may have used similar net joint torques (human + EXO) for gait. Human users adjusting their motor control to maintain consistent net joint torque when walking in the EXO may be explained by the so-called invariant torque strategy (Galle et al., 2013; Kao et al., 2010; Lewis and Ferris, 2011), in which participants use motor coordination strategies to prioritize maintaining similar net joint torques rather than joint kinematics. While both novices and experienced users required similar hip torques for walking here, experienced users achieved the necessary hip torque by deriving more EXO-generated joint torque.

Human-EXO interaction forces did not differ substantially between novices and experienced users (Fig. 5). Novices and experienced users had comparable peak interaction forces at the pelvis and foot load cells during both sessions 1 and 2, except for the fact that the time-to-peak foot interaction force during toe-off (P2), was significantly delayed for novices. In addition to this delay, there was substantially larger trial-to-trial variability among the novices (see time-series plots in Fig. A3 in the Appendix). Greater variability in novice user inputs transmitted to the EXO also seemed to have resulted in less consistency of the actuated EXO joint torques (also in Fig. A3). More importantly, the greater variability of interaction forces among novices suggests that they were still exploring strategies to interact effectively with the EXO and may not have yet converged on an optimal strategy of interaction.

We speculate that novices had not yet developed sufficient mental models of the EXO after three gait sessions. Mental models, or internal representations, refer to the capability to prepare appropriate motor commands through the prediction of forthcoming movements of the robot during the human-robot interaction. Classical studies in human motor control have shown that the success of adaptation to novel

dynamic environments is determined primarily by learning how to predict their dynamics, a process referred to as “internal model formation” (Scheidt et al., 2001; Shadmehr and Mussa-Ivaldi, 1994). Hence, the lack of an internal representation of the human-EXO system may impair the capacity to approximate the inverse dynamics resulting from human-EXO interactions (Gordon and Ferris, 2007). However, it should also be noted that novices were generally slower in walking compared to the experienced users, potentially explaining relatively lower EXO hip torques and suggesting that novices might have been less effective in interacting with EXO interfaces to provide inputs to the EXO (i.e., larger variability in EXO load cell values). Future research is warranted to investigate the factors contributing to the large variability among EXO load cell values.

Time-series plots support the notion that novices almost continuously activated their TA muscle throughout the gait cycle (Fig. 3), potentially to compensate for the inertia of the human + EXO system in a dynamic condition. On the contrary, experienced users substantially decreased TA activity after making initial heel contact until the next toe-off, adopting more burst-like activity with clear engagement and disengagement. A muscle activity pattern similar to the current novices has been observed in children while learning how to walk, wherein they initially exhibit continuous activity and gradually transition to burst activity (Chang et al., 2006). Such a shift of muscle activity, from a continuous to a burst-like pattern, has also been found in several earlier studies as participants gained more experience with exoskeleton use (Cain et al., 2007; Galle et al., 2013; Gordon and Ferris, 2007; Kao et al., 2010). One explanation for the high TA activity during the initial stages of learning observed in the current study may be due to the increased stiffness of the ankle joint to promote gait stability (Kim et al., 2021). Another explanation may simply be that novices walked with increased double support time, and this perhaps led to more continuous activity of the TA muscle.

4.4. Limitations and future work

Some limitations of the current study should be noted. First, the study had a small sample size and involved only male participants. Recruitment of participants with relatively consistent anthropometric measures was needed so that the experimental participants could fit within the EXO prototype. To be able to generalize our findings, broader samples need to be considered in the future, with different age groups, gender, and anthropometric characteristics. Second, while we identified experienced users based on heuristic criteria (i.e., the exposure period of > 3 months) and subjective opinions, it remains an open research question regarding how to define expertise in a more precise and objective manner. Third, only between-session adaptation was assessed in the current study. Having within-session adaptation results could help to gain a more comprehensive understanding of EXO motor adaptation. Fourth, motor adaptation was only evaluated during walking for three brief sessions. Hence, novices may not have reached their optimal gait patterns within the time of assessments. Longer-term EXO use and performance in a variety of tasks and environments, such as slippery surfaces and uneven terrain, must be considered to more fully understand the performance and safety aspects of such technologies. Finally, the prototype EXO was still in the developmental phases. Additional features including a fully actuated calf rotation and ankle plantar/dorsi-flexion may change the rate of learning. Despite these limitations, this is the first investigation of how novice users of a powered whole-body exoskeleton prototype adapt over time, using a comprehensive set of objective measures recorded from the human, exoskeleton, and human-exoskeleton interaction.

Directions for potential future research should also be noted. Developing more formal training protocols may facilitate efficient adaptation to the EXO. For example, providing feedback to reduce forward flexed postures and relax the plantar flexors could help novices to walk more efficiently. Further, since the level of mechanical strength

augmentation (i.e., exoskeleton assistance) affects the gait adaptation rate (Kao et al., 2010), gradually increasing EXO assistance over time may help novices to adapt more rapidly. Designing human-machine interfaces that help the user be more aware of the exoskeleton state could also improve the ease with which a human can adapt to using such complex technology. However, whether extensive training protocols are needed for users to adapt to occupational exoskeletons or whether exoskeleton design modifications should make such user adaptations unnecessary are still open questions.

5. Conclusions

In summary, our results indicate that novices did not completely adapt to the EXO within the period of use studied here (one familiarization session and three gait sessions). Although novices had spatio-temporal gait characteristics comparable to experienced users by the end of three gait sessions, important differences remained in how novices transmitted their inputs to the EXO and the subsequent commanded EXO joint torques. These differences resulted in higher levels of lower-limb muscle activity and different hip joint kinematics compared to experienced users, which persisted at the end of the study. It is possible that with additional sessions, novices could walk more like experienced users, but it is currently unclear how much additional time is required to gain such expertise. Findings from this study will help better understand the motor control and adaptation strategies exhibited by users of whole-body powered exoskeletons, guide design developments for powered exoskeletons, and help formulate training guidelines for practical whole-body powered exoskeleton use.

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The authors have no financial interests to disclose.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Figs. A1-A3

See Tables A1-A4

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