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Characterizing expert exoskeleton-assisted gait: insights to accelerate ankle exoskeleton mastery

Ava Lakmazaheri and Steven H. Collins

***Abstract*—Exoskeletons can make walking easier, but extensive training is needed to fully benefit from them, potentially hindering device adoption. Coaching new exoskeleton users to walk with energetically beneficial gait patterns might accelerate motor learning, but these target patterns have yet to be established. In this study, we characterized changes in gait biomechanics between healthy young adults' first exposure to ankle exoskeletons and after 7+ hours of training when they demonstrated full motor adaptation. We observed consistent markers of adaptation in ankle kinematics and spatial gait features; expert exoskeleton users exhibited greater ankle dorsiflexion before a powerful and concentrated push-off while walking with narrower and longer steps. Adaptations in muscle coordination patterns were more varied, but generally involved reducing co-contraction throughout the leg. By the end of training, non-propulsive exoskeleton-assisted gait features approached those of unassisted walking. Our results suggest that effective exoskeleton use involves selectively avoiding most disruptions to typical gait while accommodating energetically beneficial changes around push-off. All reported gait features can be monitored and targeted in real-time, facilitating the application of these results to reduce the time burden for novice users to maximally benefit from ankle exoskeletons.**

Keywords—exoskeletons, motor learning, gait analysis, biomechanics, adaptation.

I. Introduction

Exoskeletons are promising tools to address losses in mobility, such as those arising from age, stroke, or neurodegenerative disorders. Exoskeletons can offload assisted muscle activity and augment biological joint power, reducing the energetic cost of walking [1–3]. Making walking easier for those who struggle with mobility could promote physical activity, increasing independence, social participation, and well-being [4]. Ankle exoskeletons have particular promise for real-world use, as they can be relatively lightweight, easy to don and doff, and have been shown experimentally to provide the largest reduction in energy cost of walking of any lower-limb joint [5].

The timescale of learning to effectively use exoskeletons is slow. Healthy young adults extract full metabolic benefit of ankle exoskeletons after approximately two hours of training [6], and they continue to explore varied motor control strategies for two additional hours before achieving steady-state gait [7]. This timescale is likely to be significantly longer as people age or experience neurologically-based gait changes, given slowed or impaired motor learning [8–11]. New training approaches should be explored to ensure that the time burden of learning how to comfortably and effectively use exoskeletons is not prohibitively high.

Coaching people to walk with efficient gait patterns might expedite exoskeleton training. Prompting low-cost gait patterns for even short periods of time can aid the nervous system in identifying relevant dimensions of energy optimization in a new motor context [12]. Neither natural gait variability nor open-ended prompts to explore new coordination strategies has reliably produced initiation of energy optimization within a comparable time scale [12]. While exploration is a critical component of motor learning [6,13], insufficient knowledge about the relevant dimensions to explore could unnecessarily slow the learning process. Identifying low-cost gait patterns, in order to strategically expose people to these behaviors, could be fruitful before deploying new assistive devices.

Existing characterizations of exoskeleton-assisted gait may be insufficient to accelerate exoskeleton mastery. Lower-limb biomechanics while walking with an ankle exoskeleton have primarily been characterized after 20–30-minute training sessions. These studies found reductions in both plantarflexor activity and co-contraction of antagonist muscles, while ankle kinematics, step width, and stride time remained unchanged due to training [14–17]. Notably, motor adaptation was not characterized in these studies, and may have been ongoing. Assessing biomechanical gait changes before and after complete motor adaptation would better indicate the most relevant gait dimensions for energy optimization.

Gait biomechanics of fully adapted exoskeleton users have only been characterized for a small number of gait features selected *a priori*. In one study of users who trained extensively with exoskeletons, expertise was demonstrated by an exponential decay of gait variability to steady-state values, corresponding to a final metabolic benefit triple that of initial exposure, and the largest benefit thus far reported for use of ankle exoskeletons [6,7]. Gait adaptations reported in this study included reduced step frequency, reduced ankle angle range over the gait cycle, and reduced total plantarflexor activity [6].

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(Corresponding author: Ava Lakmazaheri.)
Ava Lakmazaheri and Steven H. Collins are with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94305 USA (emails: avalak@stanford.edu and stevecollins@stanford.edu).

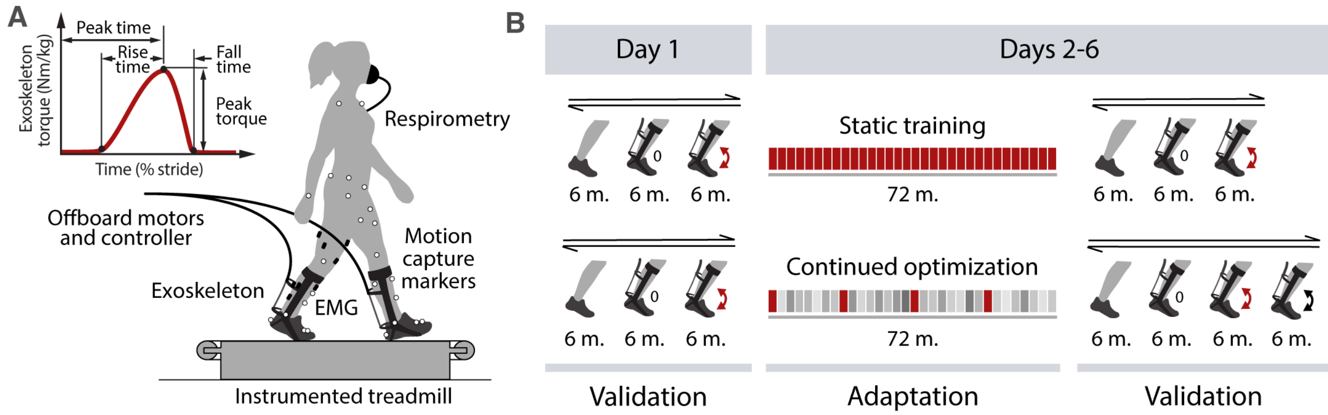

Fig. 1. Experimental setup and protocol. (A) Schematic of the experimental setup. Respirometry, motion capture, electromyography, and ground reaction force data were recorded. Exoskeleton torque was applied by off-board motors and parameterized by the magnitude and timing of peak torque, rise time, and fall time. (B) Schematic of the experimental protocol. Validation trials were performed in a double-reversal order: wearing running shoes only, exoskeletons applying zero torque, and exoskeletons applying generic assistance. In adaptation trials, the static training group (n = 5) experienced generic assistance (red) and the continued optimization group (n = 5) underwent human-in-the-loop optimization, with generic assistance tested periodically. The continued optimization group also tested optimized assistance during validation.

In this study, we performed a broader exploration of changes in gait biomechanics as the same participants—initially naïve to exoskeleton use—became expert at walking with plantarflexion assistance. We considered nine healthy young adults that trained with ankle exoskeletons over 7+ hours, and analyzed biomechanical gait data that can be monitored in real-time on a step-by-step basis: sagittal plane ankle kinematics, spatial gait features, and peak activity of lower-limb muscles. We compared changes between novices and experts, walking with and without plantarflexion assistance, to assess the relevant gait dimensions of energy optimization. We expect that this analysis can inform future work using biofeedback to guide first-time exoskeleton users toward beneficial gait patterns, expediting motor learning and improving perception of human-exoskeleton interaction.

II. Methods

A. Data Collection

Data for this study were taken from [7], with relevant details repeated here. The experimental protocol was approved by the Stanford Institutional Review Board (IRB-48749) and all participants provided written consent before participating. Healthy young adults naïve to exoskeleton use (n = 9; 3 females; age: 24 ± 3 years; body mass: 69.4 ± 10.6 kg; height: 1.73 ± 0.08 m) underwent a six-day protocol during which they walked with bilateral ankle exoskeletons at 1.25 m/s (Fig. 1). Each exoskeleton was controlled by an off-board motor, enabling the application of various high-magnitude plantarflexion torque profiles while remaining lightweight (0.88 kg). Torque profiles were parameterized by peak magnitude, peak time, rise time, and fall time (Fig. 1A).

In order to capture "novice" performance, participants first underwent six-minute pre-test trials of walking without exoskeletons, walking with exoskeletons tracking the ankle joint so as to apply negligible torque, and walking with exoskeletons applying an assistive plantarflexion torque once per step. This torque profile ("generic assistance") was set by parameters found to be widely beneficial in pilot testing: a peak magnitude of 0.54 times body weight at 52.9% stride with a rise time of 26.2% stride and a fall time of 9.8% stride. Each six-minute condition was then repeated in a double-reversal order (Fig. 1B).

Ten participants, comprising two experimental groups, were considered. Both groups experienced the same pre-test trials. The "static training" group (n = 5) then walked with generic assistance for 72 minutes in the remaining five experimental sessions. For the same duration, the "continued optimization" group (n = 5) underwent human-in-the-loop optimization [18], with a new torque profile tested every two minutes to minimize energy cost of walking. For this group, generic assistance was applied every 16 minutes to track learning (Fig. 1B). The six-minute double-reversal validation trials of no exoskeleton, unassisted, and generically assisted walking were repeated at the end of each day for both groups. The continued optimization group also walked with optimized assistance in the end-of-day validation trials. Participants each accrued 7.4 to 8.4 hours of experience with assisted walking and 8.4 to 9.4 total hours of walking while wearing the exoskeletons. Throughout the study, data were collected from an indirect calorimetry device (Cosmed Quark CPET), motion capture system (Vicon), instrumented treadmill (Bertec), and eight electromyography electrodes per leg (Delsys). One participant from the continued optimization group was excluded from our analysis due to incomplete data recording on the first day of the study.

B. Data Analysis

The distinction between novice and expert exoskeleton use was made by comparing matched validation trials between the first and last experimental session. Expert status was conferred by participants tripling their initial metabolic benefit by the end of the study [7] and by gait variability exponentially regressing to that of walking without an exoskeleton, indicating acquisition of stable motor skill [6]. Both the static training and continued optimization groups were indistinguishable by these measures. Therefore, all strides from final validation sessions were treated as

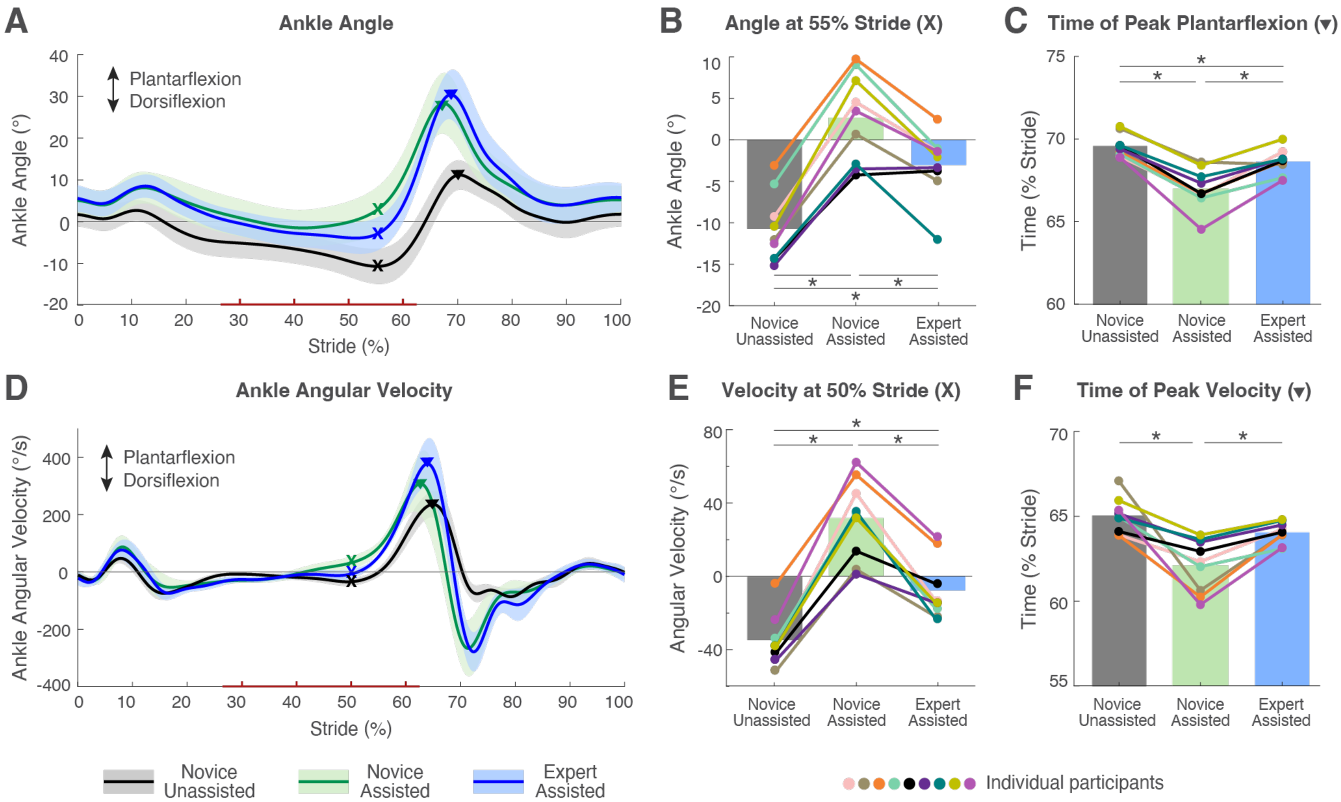

Fig. 2. Adaptations in ankle kinematics. Average (A) ankle angle and (D) ankle angular velocity profiles, measured from exoskeleton encoder. Key features of (B–C) ankle angle and (E–F) ankle angular velocity profiles across trial types. Shaded regions represent 95% confidence intervals. Red portion of axes denote when exoskeleton torque is non-zero. X denotes magnitude at 50% or 55% stride and inverted triangle denotes peak magnitude. Individual participants are represented by distinct colored circles. Asterisk signifies $p < 0.05$.

instances of expert behavior with no additional comparisons made between experimental groups. Significant difference between novice and expert gait outcomes was assessed using analysis of variance and post-hoc paired t-tests with the Bonferroni adjustment for multiple comparisons and an alpha value of 0.05.

Stride-by-stride trajectories of exoskeleton ankle angle and angular velocity were acquired through measurement from an on-board encoder. Step length and width were calculated from the position of the foot center of pressure at heel strike, measured from force plate data via the split-belt treadmill. Changes in stride duration were captured from analysis of changes in stride length given the fixed treadmill speed. Muscle activity was acquired from electromyography signals after high pass filtering at 30 Hz, rectifying, low pass filtering at 6 Hz, and normalizing to the peak activity calculated from no-exoskeleton trials in the same session. Trials with poor electromyography signal quality were excluded from analysis. Respirometry and motion capture data were not analyzed in this study, but were available for reference from this dataset.

All biomechanical profiles were normalized to percent stride, averaged across the final three minutes of each six-minute validation trial, and averaged across legs. We used visual inspection to identify features in kinematic profiles that consistently changed between novices and experts. If multiple features reflected the same gait behavior, we selected and reported one that appeared most robust to inter-subject and inter-session variability. To ensure a rigorous assessment of timing-related features, we report these analyses for biomechanical profiles both with and without normalization to stride duration.

III. Results

Ankle kinematics differed significantly between novice and expert exoskeleton users (Fig. 2). Experts dorsiflexed more mid-stride, evidenced by increased peak dorsiflexion, increased dorsiflexion at 50–55% stride, and decreased plantarflexion velocity at 50–55% stride. Natural variations in the curvature of ankle angle profiles made calculations based on peak dorsiflexion timing less consistent. Therefore, we focused our analysis on features at fixed points in the gait cycle.

Ankle angle at 55% stride was 5.7° more dorsiflexed by the end of training (Fig. 2A–B, Table 1, p = 0.01). With expertise, assisted ankle angle at this time approached that of unassisted walking (Fig. 2A–B). Novice users were 13.4° more plantarflexed when assisted than when unassisted (p = 8e-7). Expert users were 7.7° more plantarflexed when assisted than when unassisted (p = 6e-4). In general, the application of plantarflexion torque from 26.7% to 62.7% stride resulted in greater ankle plantarflexion throughout the

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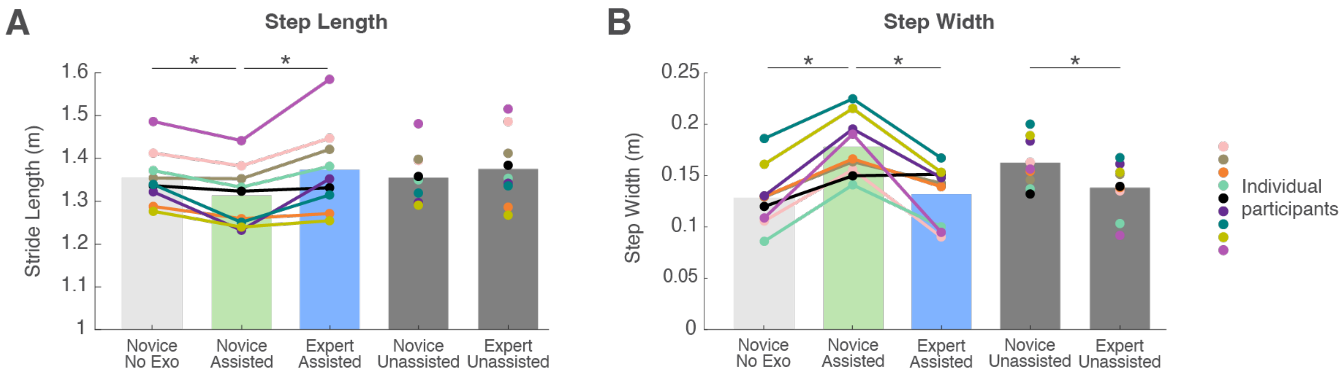

Fig. 3. Adaptations in spatial gait features. (A) Stride length and (B) step width for novice versus expert exoskeleton users across relevant trial types. Individual participants are represented by distinct colors. Asterisk signifies $p < 0.05$.

gait cycle (Fig. 2A). Unassisted ankle angle at 55% stride did not significantly change with expertise ($p = 0.4$).

All experts slowed their mid-stride ankle angular velocity (Fig. 2D–E). Expert walking with assistance corresponded to an angular velocity at 50% stride that was 39.2°/s slower than that of novices (p = 6e-4). With training, assisted angular velocity at 50% stride approached that of unassisted walking (Fig. 2D–E). Assistance resulted in a 66.2°/s speed increase during initial exposure (p = 2e-6) and 27.0°/s increase from baseline during final exposure (p = 2e-4). Expert ankle angular velocity without assistance was also 12.7°/s increased from baseline ($p = 0.01$).

Experts also shifted ankle kinematics to delay timing of toe-off. This shift was reflected in the later timing of peak plantarflexion and dorsiflexion angles, peak plantarflexion velocity, and transition times between plantarflexion and dorsiflexion for both angle and velocity profiles. In addition to the inconsistencies in peak dorsiflexion timing described previously, the transition from plantarflexion to dorsiflexion could not be reliably reported as differences in exoskeleton fitting across sessions caused artificial shifts in ankle angle at heel strike for some participants. Therefore, we focused analysis on the timing of peak plantarflexion angle and peak plantarflexion velocity.

Peak plantarflexion angle shifted later in stride as participants adapted to exoskeleton assistance (Fig. 2C, Table 1). Expertise corresponded to a peak plantarflexion angle 1.5% or 40 ms later in stride ($p = 0.01$ and p = 4e-4, respectively). Changes in peak plantarflexion timing approached participants' unassisted baseline with training (Fig. 2C): from 3.0% or 50 ms earlier on initial exposure ($p = 0.003$ and p = 3e-6, respectively) to 1.5% or 6 ms earlier on final exposure ($p = 0.02$ and $p = 1$, respectively). Peak plantarflexion timing during unassisted walking did not significantly change with expertise ($p = 0.7$ and $p = 0.06$ with and without stride normalization, respectively).

Peak ankle angular velocity also consistently shifted later in stride as people adapted to assistance, by an average of 1.2% stride or 46 ms (Fig. 2F, Table 1, $p = 0.01$ and p = 5e-4, respectively). As users adapted, their peak velocity timing during assisted gait approached their baseline timing during unassisted gait: from 2.0% or 53 ms earlier on initial exposure to 0.8% or 7 ms earlier on final exposure (Fig. 2F, $p = 0.004$, p = 4e-4, $p = 0.3$, $p = 0.9$, respectively). Peak velocity timing during unassisted walking did not significantly change with expertise ($p = 0.1$ and $p = 0.09$ with and without stride normalization, respectively).

All experts increased their stride length such that, on average, assisted strides were 6.0 cm longer after training (Table 1, Fig. 3A, $p = 0.02$). Compared to walking in normal shoes, assistance resulted in a 4.1 cm shortening of stride for novices and a 1.9 cm lengthening of stride for experts (Fig. 3A, $p = 0.01$, $p = 0.9$, respectively).

Step width decreased significantly with training. Expertise resulted in a 4.6 cm narrowing of step width when walking with assistance (Table 1, Fig. 3B, $p = 0.005$). Expertise also corresponded to a 2.4 cm narrowing of step width when walking without assistance (Fig. 3B, $p = 0.04$). After sufficient training, assisted step width approached baseline values of walking in normal shoes. Initially, assisted steps were 5.0 cm

TABLE I. BIOMECHANICAL GAIT FEATURES (MEAN ± STANDARD DEVIATION) DURING ASSISTED WALKING PRE- AND POST- ADAPTATION.

Gait Features	Novice	Expert	p
Ankle angle at 55% stride (º)	2.7 ± 5.4	-3.0 ± 4.0	0.01
Peak ankle angle time (% stride)	67.0 ± 1.3	68.7 ± 0.8	0.01
Ankle angular velocity at 50% stride (º/s)	31.5 ± 21.6	-7.7 ± 16.6	6e-4
Peak ankle angular velocity time (% stride)	62.1 ± 1.2	64.0 ± 0.6	0.01
Stride length (m)	1.31 ± 0.07	1.37 ± 0.10	0.02
Step width (m)	0.18 ± 0.03	0.13 ± 0.03	0.005
Peak med. gastroc. activity (%)	102.5 ± 14.1	100.4 ± 14.8	0.6
Peak lat. gastroc. activity (%)	83.0 ± 24.8	77.5 ± 18.5	0.5
Peak soleus activity (%)	65.7 ± 10.0	66.0 ± 10.8	0.9
Peak tib. ant. activity (%)	127.3 ± 29.7	110.6 ± 14.5	0.03
Peak rectus fem. activity (%)	122.8 ± 31.0	97.7 ± 8.9	0.02
Peak vastus med. activity (%)	92.2 ± 21.5	95.9 ± 9.5	0.7
Peak biceps fem. activity (%)	130.3 ± 40.7	112.4 ± 46.9	0.1
Peak semiten. activity (%)	91.6 ± 22.5	93.2 ± 14.8	0.7

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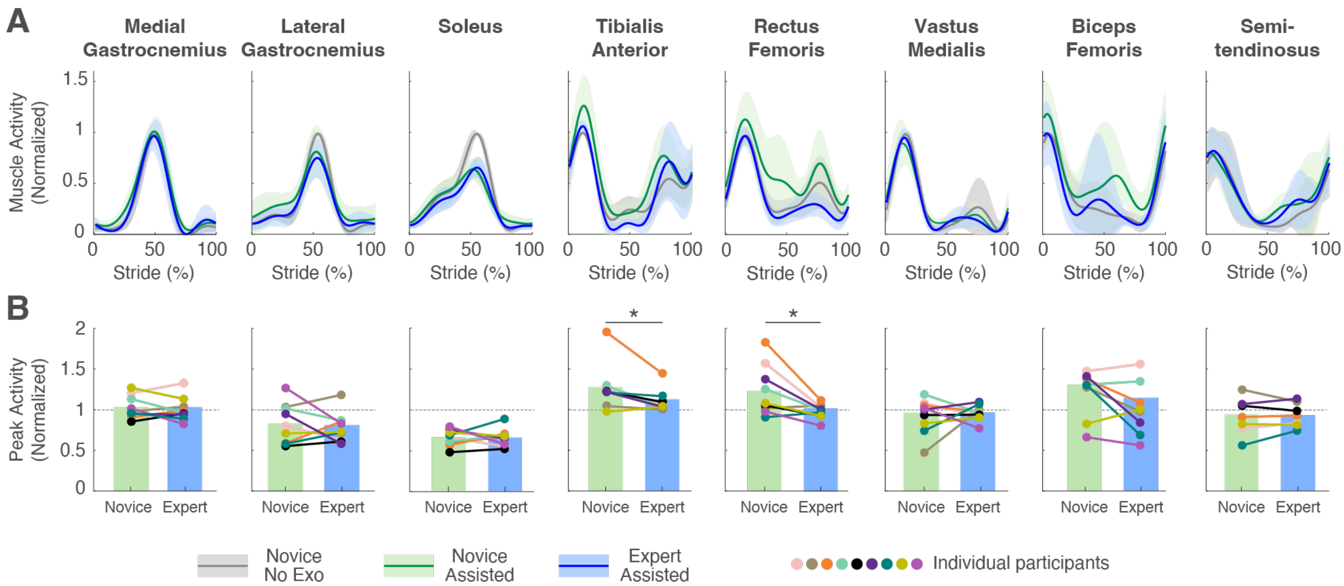

Fig. 4. Changes in muscle activity between novice and expert exoskeleton users. (A) Profiles of recorded muscle activity, averaged across subjects and between legs. All profiles are normalized to values from walking without exoskeletons. Green and blue graphs represent novice and expert exoskeleton-assisted trials, respectively. Gray curves represent novices walking with no exoskeleton. Shaded regions show 95% confidence interval. (B) Changes in peak magnitude of normalized muscle activity with expertise. Individual participants are represented by distinct colors.

wider than in no-exoskeleton gait (p = 1e-4) and, ultimately, only 0.3 cm wider (p = 1).

Some differences in muscle coordination patterns were observed between novice and expert exoskeleton users. The strategy to reduce energy consumption by offloading muscles assisted by the exoskeleton was not unique to experts, reflecting results from prior short duration studies [6,14–17]. In this dataset, peak muscle activity was similar between novices and experts for the medial gastrocnemius, lateral gastrocnemius, soleus, vastus medialis, and semitendinosus (Fig. 4, Table 1). Novices had relatively high activation in the tibialis anterior, rectus femoris, and biceps femoris compared to walking without an exoskeleton, indicating high stiffness throughout the leg. Experts generally reduced this stiffness via lowered activity of the rectus femoris (122.8% vs. 97.7%, p = 0.02) and tibialis anterior (127.4% vs. 110.6%, p = 0.03). Activity in the biceps femoris also decreased, though this effect was not statistically significant (130.3% vs. 112.4%, p = 0.1). Inter-subject variability of muscle coordination patterns was high overall, and trends in changing peak activity were not consistent across participants (Fig. 4B).

IV. Discussion

We identified several biomechanical gait changes that occurred as novice exoskeleton users adapted to plantarflexion assistance. Changes in ankle kinematics and spatial gait features were highly consistent across participants. Changes in muscle coordination patterns were more variable, but the tendency for experts to decrease co-contraction throughout the leg appeared meaningful. Most reported changes emerged later in training than has previously been tested [14,16,17], indicating the importance of sufficient exposure to capture behaviors emerging over long or unknown timescales. The gait features we identified can be monitored and targeted in real time using wearable sensors and biofeedback, making them promising tools to elicit energetically efficient gait behaviors in new exoskeleton users.

Kinematic adaptations appeared to improve the efficiency of push-off. Novices generated positive plantarflexion velocity as exoskeleton torque was rising, causing plantarflexor muscles and tendons to shorten before significant power was needed for toe-off. In contrast, experts actively dorsiflexed, generating negative work, during this portion of stride (Fig. 2). Experts' lower metabolic cost is likely explained in part by eccentric muscle contractions generating force more efficiently than concentric contractions, and lengthening Achilles tendons enabling greater elastic energy storage and release [2,19].

Changes in step length and width throughout training could reflect task priorities shifting from maintaining balance to minimizing energy cost. Optimization of foot placement typically accounts for several objectives, including energy cost, stability, and maneuverability [20,21]; each objective may progress with a unique timescale [6,22]. For these participants, adaptations in step frequency variability—an indicator of dynamic balance [23]—occurred twice as quickly as adaptations in step frequency [6]. Participants may have initially responded to torque-induced perturbations of their typical gait by placing their feet further apart mediolaterally and closer to their base of support anteroposteriorly [21,24]. Once balance was more easily maintained, participants may have reduced step width to minimize the energetic cost of redirecting center of mass velocity during step-to-step transitions [21] and increased step length to mitigate the high energetic penalty of swing [25].

With experience, most participants' gait features shifted toward baseline values from unassisted or no-exoskeleton walking. Expert exoskeleton users reduced disruptions to gait when no energetic benefit was provided: increased plantarflexion throughout stride, wider stance, shorter steps, and greater co-contraction for stabilization. Simultaneously, experts preserved exoskeleton-induced gait changes that provided energetic benefits, namely offloading plantarflexor activity and stretching the plantarflexor muscle-tendon units before a powerful push-off. Future research should explore if this trend persists for groups other than healthy young adults, whose baseline gait patterns may be less energetically optimal.

Our findings suggest that short bouts of walking may be sufficient for individualization of desired exoskeleton-assisted gait behaviors. For each participant, step length and width generally returned to values observed during no-exoskeleton pre-test trials (Fig. 3). Experts' step lengths consistently exceeded baseline values by an average of 2 cm, likely due to the increased penalty of swing with the exoskeleton's added distal mass and medial envelope. Kinematic features did not revert to participants' initial values from unassisted walking, but did consistently progress toward the approximate average of unassisted and assisted baseline values (Fig. 2). Supplemental analysis showed that kinematic changes plateaued before the final experimental session, suggesting that these values would change minimally with additional training, and that the remaining offset is due to limits created by human-exoskeleton interaction. Given the high inter-subject variability of absolute gait outcomes and the consistency of trends across trial types (Fig. 2–3), we believe that prompting changes toward one's own unassisted or no-exoskeleton baseline will likely be more effective than trying to induce any absolute gait outcome.

A portion of the observed gait changes were attributed to learning to walk while wearing the exoskeletons alone. Gait compensations to the added medial envelope and mass of the device presented in both unassisted and assisted walking trials (Fig. 3). This suggests that training to adapt to wearing a new device is partially separable from training to adapt to assistance. Beginning with unassisted training might prove more tractable for novices learning to use exoskeletons that are particularly large, heavy, or restrictive of typical joint kinematics.

This study is limited by high inter-subject variability and a relatively small sample size. Findings may vary with additional or demographically distinct participants. We could not reliably calculate an ideal magnitude of change for each gait outcome, if such an absolute measure exists. However, the consistency of trends across participants strongly indicates that these are important dimensions for people to adapt along. Analyzing motion capture data could provide more detailed insights into adaptations occurring throughout the leg, and reveal more about the complex mechanisms underlying reduced metabolic cost of walking with exoskeletons.

Further research is needed to evaluate the generalizability of these findings. The observed trends reflect behavior from one lightweight, torque-controlled ankle exoskeleton assisting plantarflexion. Use of an ankle exoskeleton with a different mechanical design and control will likely affect the magnitude of changes between novices and experts. However, we expect the direction of the observed trends to remain consistent for other ankle exoskeletons given the similarity between early behavior in this study and outcomes of prior ankle exoskeleton research [6,14–17]. The spatial gait changes observed in this study were also consistent with the metabolic determinants of step length and width in simple walking models when accounting for the added penalty of distal mass and medial obstructions [21,25], suggesting that similar effects may occur during adaptation to other types of wearable robots.

Our future work will coach novice exoskeleton users to exhibit the expert gait biomechanics identified in this study. Kinematic, spatiotemporal, electromyographic, and metabolic changes co-occurred throughout the experimental protocol, but an immediate metabolic benefit from adopting the identified gait changes has not been demonstrated. Differences in timescales between neuromechanical and metabolic adaptations in this dataset [6,7] and others [22,26] suggest complex mechanisms of reducing whole-body metabolic cost. If it is shown that large energetic benefits can be extracted without extensive self-guided gait exploration, this could prove an effective technique for expediting required exoskeleton training times. Future work can additionally apply this approach to characterize biofeedback targets for expert use of a wide range of assistive devices.

V. Conclusions

There are consistent biomechanical differences in how people walk with ankle exoskeletons at the beginning and end of motor adaptation. Identified changes included dorsiflexing more preceding a later push-off, taking narrower and longer steps, and mitigating high levels of co-contraction throughout the leg. This study reveals that relatively subtle changes in human-exoskeleton interaction can correspond to large changes in energy cost of walking. However, these improvements take a long time for healthy young adults to discover when only subject to natural gait variability. Leveraging our results to coach new exoskeleton users toward the identified gait changes could reduce the time needed for people to extract maximum benefit from exoskeletons. Improving human-device interaction during training may increase user acceptance of exoskeletons for those who could benefit from them most.

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