Retention of Performance Following Removal of Visual Feedback of Trailing Limb Angle in Exoskeleton-Assisted Gait

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Introduction

Ankle exoskeletons (EXOs) represent an innovative approach to enhancing propulsion during walking, offering significant potential as assistive devices for people with mobility deficits. Propulsion during gait is largely influenced by both ankle plantarflexion torque and trailing limb angle (TLA)[1], and ankle EXOs can specifically enhance plantarflexion torque. Ankle EXOs have been widely studied for limb propulsion augmentation in various patient populations.[2-5] In many of these cases, however, individuals instructed to walk with an ankle EXO appear to instinctively decrease their TLA[4,5], and/or reduce their biological ankle torque, possibly to maintain a consistent total ankle torque.[2,3] These compensatory adjustments by the person can hinder the potential for the EXO to fully augment propulsion, thereby reducing its effectiveness in improving gait performance. Therefore, to maximize the benefits of the EXO, it is crucial to develop effective methods to teach users to avoid compensatory strategies and promote device-assisted propulsion.

To effectively promote device-assisted propulsion and avoid compensatory strategies, integrating motor learning principles is required. Use-dependent learning is characterized by a change in motor behavior driven by repeated task-practice, such as is utilized with treadmill training.[6] Lasting improvements from use-dependent learning are slow to accumulate and may take several weeks to months to develop, however, when combined with instructive learning, more rapid changes in motor behavior can occur.[7] Instructive (strategic) learning occurs when external feedback on movement errors guides the development of an intentional strategy to improve task performance.[8,9] Instructive learning is largely explicit in nature, however, learning processes rarely occur in isolation, and behavior reflects that of multiple learning processes.[10] As an example, gait training with real-time visual biofeedback combines the principles of use-dependent and instructive learning and has been studied as a method of modifying gait performance in many patient populations.[11-13]

For visual feedback to be an effective tool for motor learning for clinical populations, the acquired skills induced by feedback should be retained at least in the short-term. Past work has shown that able-bodied individuals may demonstrate short-term retention of modified gait patterns following a short period of biofeedback training.[14] However, it is also known that explicit, strategic learning processes decay quicker than implicit processes.[8] Additionally, some of the target populations that might benefit from ankle EXOs, such as post-stroke individuals, may have decreased motor learning capacities and reduced responsiveness to biofeedback compared to unimpaired individuals.[15] We are unaware of evidence of any short-term retention of gait changes induced by visual feedback during EXO-assisted walking despite the important implications of this technique for teaching people how to use EXOs.

Therefore, the purpose of this study was to determine the effects of visual feedback of trailing limb posture on the adjustment and retention of TLA and propulsion in EXO-assisted gait. We hypothesized that: (1) given short-term exposure to instructive learning with visual biofeedback, unimpaired individuals will retain improvements in TLA and propulsion after the removal of feedback, but (2) the increases in TLA and propulsion performance will shift towards baseline due to the short-term training period interfering with the restoration of default gait pattern.

Methods

Participants/Recruitment

We recruited 10 young, unimpaired individuals for this study. Participants were included if they reported being able to walk uninterrupted for 20 minutes without assistance and without self-reported uncontrolled cardiovascular, respiratory, or metabolic problems. All participants were required to have normal or corrected to normal vision. Participants were excluded if they self-reported orthopedic or neurological disorders that may alter gait mechanics, a history of balance deficits, or uncontrolled seizures. Participants provided written, informed consent to participate in this study approved by the University of North Carolina at Chapel Hill Institutional Review Board.

Data Collection

We collected kinematic data at 120 Hz using marker-based motion capture (Vicon, Los Angeles, CA) and sampled synchronized ground reaction forces (GRFs) at 960 Hz from a dual-belt instrumented treadmill (Bertec Corp, Columbus, OH). Prior to data collection, we placed 14 mm retro-reflective markers bilaterally on the second metatarsal head, fifth metatarsal head, center of the posterior calcaneus, medial and lateral malleoli, medial and lateral femoral condyles, greater trochanter, and iliac crest. Clusters of four markers were placed on the posterolateral shank and thigh, and a three-marker cluster was placed on the anterior pelvis to accommodate the EXO motor that rested on the posterior pelvis. We calculated TLA as the angle between the laboratory's vertical axis and a line connecting the markers placed on the greater trochanter and the fifth metatarsal head.[1,16,17] Prior to the trial start, participants practiced with the biofeedback in standing or walking to ensure understanding of feedback mechanism and the ability to control TLA voluntarily.

For all conditions, participants walked on the treadmill at 1 m/s, while wearing a bilateral powered ankle EXO (Biomotum SPARK, Portland, OR) providing plantarflexion torque to the right limb only (termed the training limb).[18-20] We started testing by obtaining the participants' baseline TLA of the training limb from a 50 s control walking trial, while they wore the EXO in an unpowered (i.e., passive) state. Using a block-randomized design, we then provided real-time visual feedback of training limb TLA (baseline, baseline + 5°, or baseline - 5°) via a TV monitor with the target TLA displayed as a horizontal green band with a ± 1° height (Fig 1). Within each TLA condition, participants walked with three levels of EXO assistance (0%, 15%, and 35% BW plantarflexion torque) in a randomized order. During all trials, participants walked continuously, first for 50 seconds with visual feedback and verbal instructions to 'reach the target with each step,' followed immediately by 50 seconds without feedback. During the no-feedback period, participants were instructed to 'just keep walking,' with the additional guidance to 'walk however feels most natural' if they asked for clarification. Participants were allowed to rest as needed (~5 minutes) between target TLA conditions.

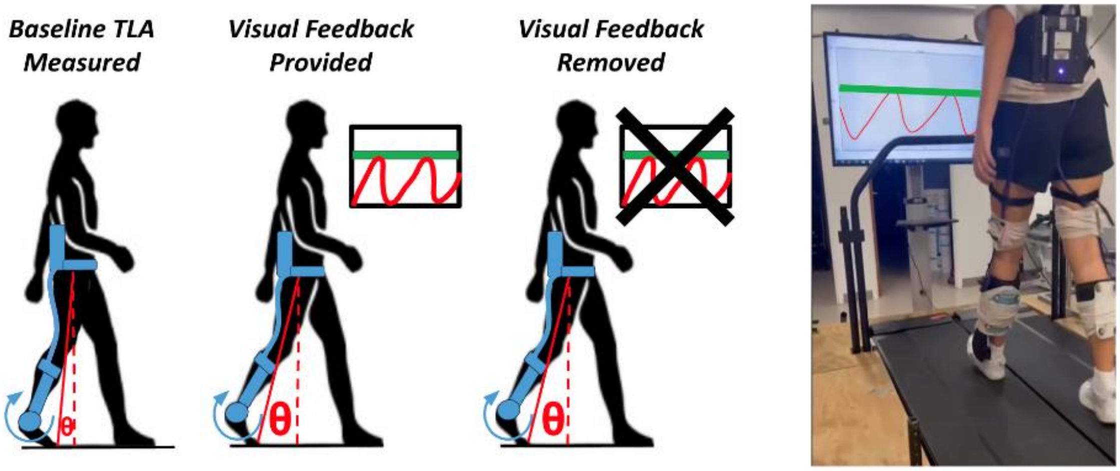

Figure 1. Schematic showing the study design and real-time visual feedback mechanism. TLA angle on y-axis and real-time TLA displayed in red with green band with ± 1° height as target.

Data Processing

GRFs were filtered using a 4th-order low-pass Butterworth filter with a 20 Hz cutoff frequency and normalized to participants' body weight (BW). Propulsive impulse was calculated as the time integral of the positive anteroposterior component of the GRF vector over each gait cycle.[21] Marker trajectories were filtered using a 4th-order low-pass Butterworth filter with a 6 Hz cutoff frequency. Anterior-posterior (AP) and medial-lateral (ML) margin of stability (MoS) at training limb toe-off was calculated in accordance with the conventions described by Curtze et al.[22] In the AP direction, a negative value indicates that the base of support (BOS) lies posterior to the extrapolated center of mass (XcoM). When normalized to baseline, a positive change reflects a reduced magnitude AP MoS and reduced stability, whereas a negative change reflects an increased magnitude AP MoS and greater stability. In the ML direction, a positive value indicates the BOS is located lateral to the XcoM, and a negative value indicates the BOS is located medial to the XcoM.

Statistical Management and Analysis

For each outcome measure (i.e., peak TLA, propulsive impulse, and MoS), we computed the average of the final five training limb gait cycles during both the feedback and no-feedback conditions to arrive at a representative value for each participant. The subject's averaged data from both the feedback and no-feedback conditions was then normalized to the average values obtained from the control condition. All data were then analyzed using SPSS (v29; Chicago, IL). All outcomes were computed for the training limb and compared across conditions with a 3-way (TLA vs EXO torque vs FB) repeated measures ANOVA. Paired t-tests were used as post-hoc tests with a Bonferroni correction for multiple comparisons. Data were lost for one condition for one participant (target TLA = baseline - 5°, prescribed EXO torque = 15% BW) and replaced with multiple imputation using a MATLAB custom function developed by Folch-Fortuny et al.[23]

Results

Participants

Of the 10 participants recruited (5 female, 5 male), two were excluded from analysis for not completing the full protocol. The final analysis included 8 participants (3 female, 5 male) with an average age of 21 ± 1.8 years, height of 1.76 ± 0.12 m, and mass of 71.0 ± 17.7 kg.

Change in Peak TLA

Overall, participants adjusted their TLA with visual feedback and retained some adaptations even after feedback was removed (Fig 2). We observed a main effect of target TLA ($p < 0.001$, $\eta_p^2 = 0.943$) and EXO torque ($p = 0.018$, $\eta_p^2 = 0.438$) on change in peak TLA. The presence of feedback, however, did not impact TLA ($p = 0.537$, $\eta_p^2 = 0.057$). We did observe an interaction effect between target TLA and the presence of feedback on the change in TLA (p =

0.043, η_p^2 = 0.452). Post-hoc testing revealed that the change in peak TLA during the baseline condition remained close to the control condition both with ($\bar{x}$ = 0.11°) and without ($\bar{x}$ = 0.40°) feedback. In the baseline + 5° condition, however, the change in peak TLA was greater at the end of the feedback period (+4.6 ± 0.89°) compared to what was observed at the end of the no feedback condition (+3.3 ± 1.8°, p = 0.002). We observed a similar pattern when participants walked with the baseline - 5° condition, in which the change in peak TLA with feedback was further from control (-3.3 ± 1.5°) than it was when feedback was removed (-1.9 ± 1.4°, p = 0.001).

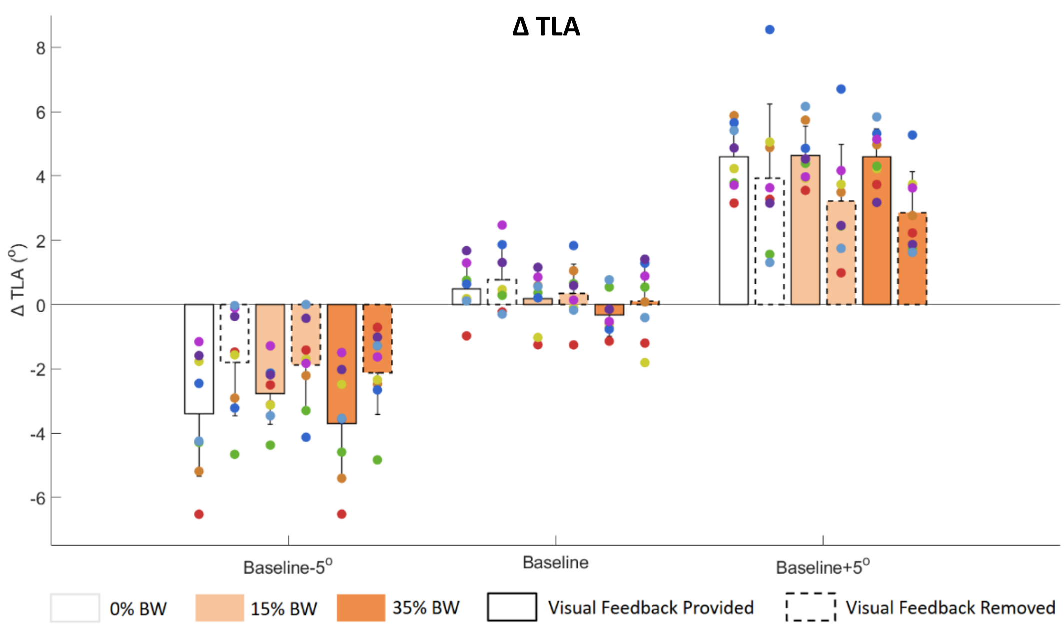

Figure 2. Change in TLA from the control condition to the feedback condition compared to the change from the control condition to the no-feedback condition. Individual data points are represented as dots and bar graph represents the condition mean. The error bars represent the standard deviation.

Change in Propulsion

We did not observe a main effect of feedback condition (p = 0.347, η_p^2 = 0.127) or EXO torque (p = 0.302, η_p^2 = 0.157), and no interaction effects were noted for changes in propulsive impulse (see Figure 3). However, a main effect of target TLA was observed (p < 0.001, η_p^2 =

0.883), such that when the larger target TLA was prescribed, propulsive impulse was 0.15 ± 0.005 Ns/BW greater than baseline at the end of the feedback period and 0.12 ± 0.008 Ns/BW at the end of the no feedback period. This difference between feedback and no feedback conditions was greater than what we observed when the smaller target TLA was prescribed. Specifically, during the baseline - 5° condition we observed a change in propulsive impulse of –0.007 ± 0.006 Ns/BW at the end of the feedback period and a comparable change of –0.003 ± 0.004 Ns/BW at the end of the no feedback period.

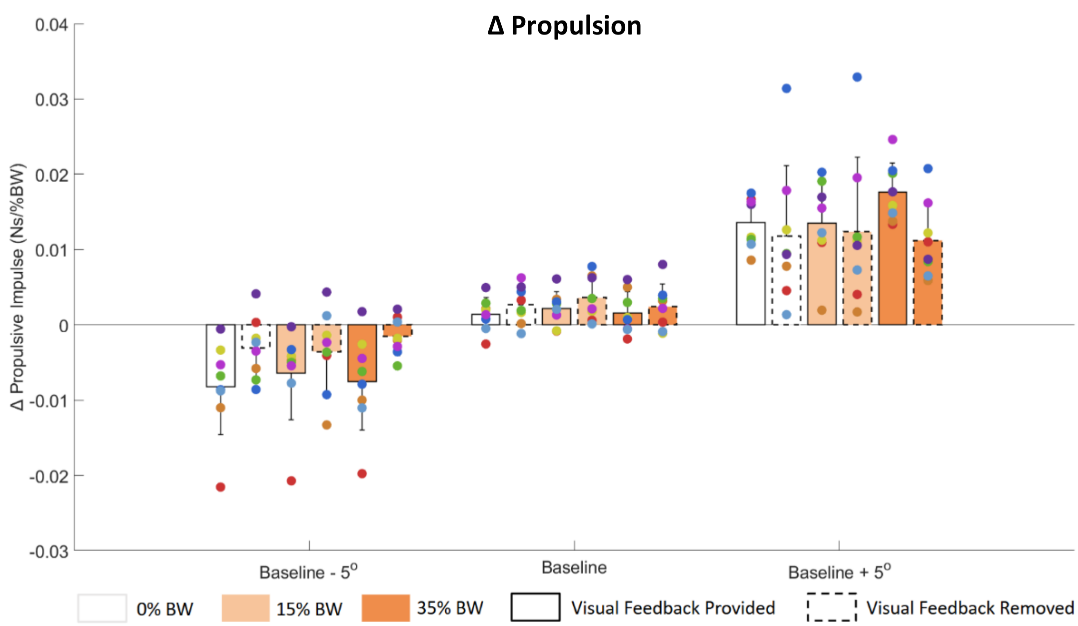

Figure 3. Change in propulsive impulse from the control condition to the feedback condition compared to the change from the control condition to the no-feedback condition. Individual data points are represented as dots and bar graph represents the condition mean. The error bars represent the standard deviation.

Margin of Stability (MoS)

For the change in AP MoS relative to control, we observed that both target TLA ($p < 0.001$, $\eta_p^2 = 0.854$) and prescribed EXO torque ($p < 0.001$, $\eta_p^2 = 0.698$) had main effects on the outcome. Although we saw a main effect of EXO torque & target TLA, there was a 3-way interaction between EXO torque, target TLA, and the presence of feedback ($p = 0.006$, $\eta_p^2 = 0.395$). This 3-way interaction was likely influenced by a 2-way interaction of target TLA and feedback ($p = 0.046$, $\eta_p^2 = 0.431$). We observed that as target TLA values increased, AP MoS became less negative, resulting in a decrease in its magnitude. This led to a positive change in AP MoS for the large target TLA and a more negative change for the small target TLA (Fig 4). Post-hoc tests revealed all comparisons were statistically significant. The opposite was seen with prescribed EXO torque, with a positive change in AP MoS with no EXO assistance (+0.008 m from baseline) and a negative change in AP MoS with 35% BW assistance (-0.005 m from baseline). The change in AP MoS values moved towards baseline following removal of feedback during both the large and small TLA conditions. However, we observed that the AP MoS values increasingly moved towards baseline with large target TLA and with increasing EXO assistance, whereas with small target TLA, AP MoS values moved towards baseline with decreasing EXO assistance (Fig 4).

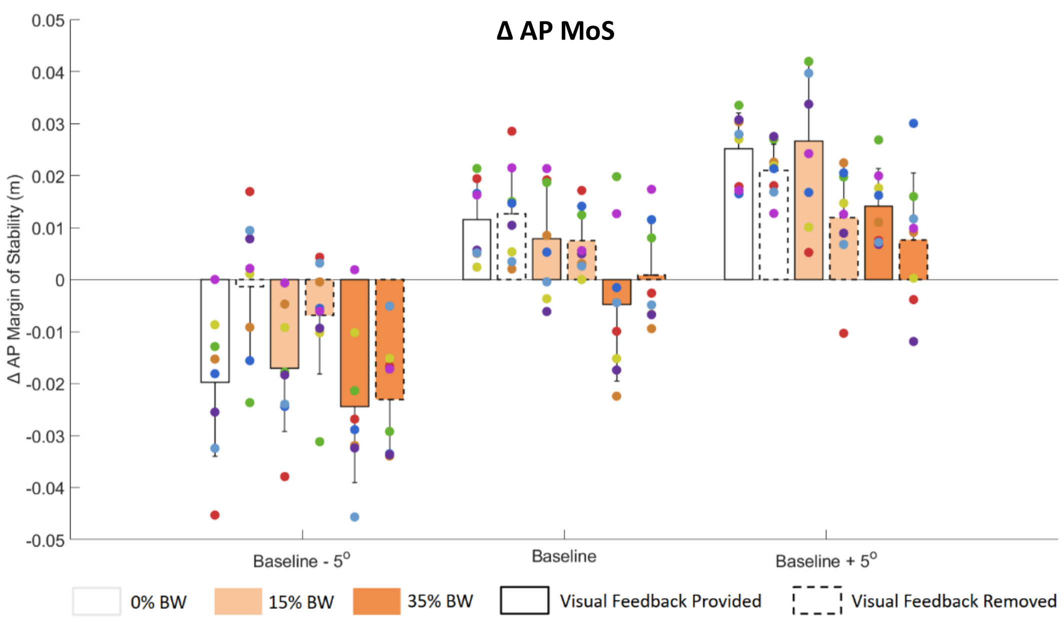

Figure 4. Change in AP MoS from the control condition to the feedback condition compared to the change from the control condition to the no-feedback condition. Individual data points are represented as dots and bar graph represents the condition mean. The error bars represent the standard deviation.

For change in ML MoS, target TLA had a main effect on the outcome ($p < 0.001$, $\eta_p^2 = 0.883$). No main effect was observed of EXO torque or presence of feedback and no interaction effects observed.

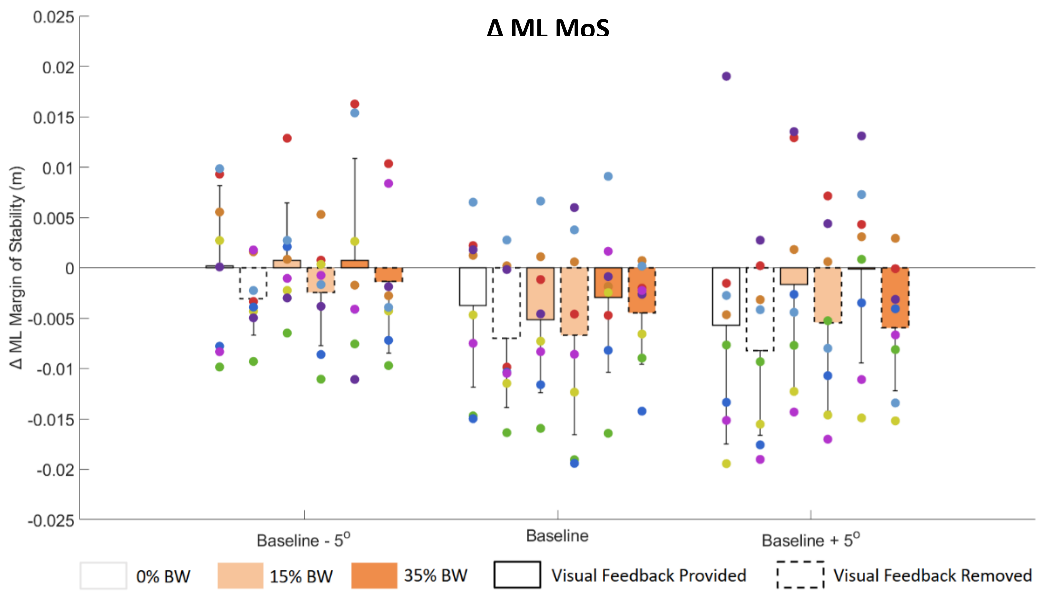

Figure 5. Change in ML MoS from the control condition to the feedback condition compared to the change from the control condition to the no-feedback condition. Individual data points are represented as dots and bar graph represents the condition mean. The error bars represent the standard deviation.

Discussion

The purpose of this study was to determine the effects of removing visual feedback of trailing limb angle on the retention of gait propulsion in exoskeleton-assisted gait with unimpaired individuals. Overall, we observed that there is short-term retention of propulsion adjustments despite removal of visual feedback of trailing limb angle, supporting our hypothesis. Nevertheless, target TLA performance decreased once feedback was removed, potentially due to changes in stability. Our findings suggest that unimpaired individuals can adjust their gait biomechanics in response to visual feedback, specifically TLA and propulsion, and retain some of these changes even when feedback is removed. Overall, these data have implications for teaching patients how to walk with an exoskeleton.

Participants retained increases in propulsion despite a gradual reduction in TLA after feedback removal, partially supporting our first hypothesis that unimpaired individuals will retain improvements in TLA and propulsion after the removal of visual feedback. This suggests that while learned TLA performance was not fully preserved, some beneficial gait adaptations were maintained. The absence of a main effect of the presence of feedback on propulsive impulse values implies that individuals may have compensated using other gait strategies, such as modulating ankle moment[1], to sustain propulsion even as TLA declined, although we did not analyze these data. However, trailing limb angle has been shown to contribute twice as much to propulsion as ankle moment[1], suggesting that there were changes to the ankle moment as feedback was removed and TLA started to return to baseline. Therefore, it may be pertinent to explore other gait mechanisms that may have contributed to this trend in future studies.

Our second hypothesis, that performance would begin trending back toward baseline due to the short exposure to feedback, was supported. TLA performance declined once feedback was removed, and propulsion shifted toward baseline, albeit less sharply. We suspect that the presence of gait instability may have influenced this observation. Specifically, as TLA increased, participants' anterior-posterior MoS became less negative, suggesting reduced stability; conversely, smaller TLA values were associated with more negative AP MoS, indicating greater stability. Prior studies have linked shorter steps with increased AP stability[24-26,] reinforcing the idea that stability constraints may lead to limited TLA retention of large TLA feedback cues. However, the three-way interaction effect on AP MoS suggests that EXO condition may contribute to this finding. Namely, as plantarflexion assistance increased, AP MoS shifted toward more negative values, suggesting enhanced stability. In the condition combining high assistance (35% BW) with a small TLA target (baseline – 5°), the difference in AP MoS between the feedback and no feedback period was smallest (-0.004 m), potentially reflecting the most stable environment for learning and retention, albeit perhaps not optimal for maximizing limb propulsion. These insights may contribute to future efforts to pinpoint which factors most strongly influence the retention of learned skills.

EXO condition also had a main effect on TLA adherence and AP MoS, but not on propulsion. Greater EXO assistance made it more difficult to maintain a large TLA once feedback was removed, likely due to constraints imposed by a fixed walking speed at 1.0 m/s. With greater plantarflexion torque and no opportunity to increase gait speed, participants may have been limited in their ability to maintain a larger TLA. This was likely a significant limiting factor in determining true retention of skills induced by feedback, and future studies should seek to address this by using overground walking or speed-adaptive treadmills[27] to reduce these constraints. It is important to note that because our participants were unimpaired, they did not have any deficits in biological ankle torque that required EXO augmentation. In populations with notable loss of plantarflexion and a propulsive reserve, like people post-stroke[28] or unimpaired older adults[29], it is possible we would have seen more of an effect of EXO torque on propulsion.

Limitations

The purpose of the study was to investigate the interaction between EXO assistance and TLA feedback, and therefore the walking conditions were too short to observe any true adaptation to the device. Previously established training requirements for adaptation to an ankle EXO suggest about 25 minutes[3] to 110 minutes[30] of walking, and previous work suggests multiple training sessions are required to induce motor learning effects.[31] As such, our study created less opportunity for retention due to the short training period. Additionally, data were not collected continuously between feedback and no feedback periods, resulting in an undetermined amount of time (approximately 10 seconds) following feedback removal and the onset of no feedback data for each condition. This limited our ability to evaluate the trajectory of performance changes over time. Future iterations of this study will incorporate continuous data collection to address this limitation.

Conclusions

This study demonstrates that unimpaired individuals can modulate trailing limb angle (TLA) and propulsion in response to visual biofeedback while walking with an ankle exoskeleton and retain some of these performance gains after feedback is removed. However, performance gradually returned toward baseline, suggesting that short-term exposure to feedback may be insufficient to override default gait patterns. Stability, as measured by anterior-posterior margin of stability (AP MoS), may have contributed to this observation, especially in conditions with less exoskeleton assistance and a greater target TLA. These findings underscore the importance of considering both stability and assistance level when designing feedback-based interventions for exoskeleton-assisted gait. Future studies should explore longer training durations and various clinical populations to better understand the mechanisms underlying retention and optimize training strategies for lasting benefit.

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