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Full Length Article

Gradually learning to increase gait propulsion in young unimpaired adults

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ABSTRACT

Distorted visual feedback (DVF) may employ both implicit and explicit approaches to enhance motor learning. Our purpose was to test the effect of DVF of gait propulsion on the capacity to alter propulsive forces, and to determine the biomechanical determinants of propulsion. Seventeen young unimpaired individuals walked for three minutes of baseline (no feedback), then completed three randomly ordered, 10-minute Learning conditions: Real, 10DVF, and 20DVF. During the DVF conditions, we gradually decreased the feedback value without the participants' knowledge. For all Learning conditions, participants were instructed to maintain the propulsive force between two targets representing ±1 standard deviation as obtained from baseline. A one-minute retention trial without any feedback was performed immediately after Learning. Participants increased propulsive forces and trailing limb angle in both DVF conditions that persisted through retention; however, no change in ankle plantarflexion moment was noted. These findings offer promise of translation to clinical populations with propulsion deficits and require combined implicit and explicit learning components.

1. Introduction

The presence of gait impairments after a neurologic injury represents a considerable challenge for patients and rehabilitation professionals. For many pathologies, deficits in muscle force-generating capacity and motor coordination can lead to reduced limb propulsion (Bowden, Balasubramanian, Neptune, & Kautz, 2006; Mahon, Farris, Sawicki, & Lewek, 2015), which is the anteriorly directed ground reaction force responsible for generating the body's forward progression during gait. As a result, gait compensations can contribute to slow and metabolically costly walking (Farris, Hampton, Lewek, & Sawicki, 2015). Increased propulsion is associated with increased walking speed (Hsiao, Knarr, Higginson, & Binder-Macleod, 2015), which has the potential to increase community participation and quality of life (Schmid et al., 2007). Addressing deficits in limb propulsion, therefore, represents an urgent need for many patient populations, although learning how to increase propulsion remains a challenge.

The use of visual feedback represents a powerful tool for motor learning (Binder, Moll, & Wolf, 1981; Franz, Maletis, & Kram, 2014; Liu, Kim, Wolf, & Kesar, 2020; Phanpho, Rao, & Moffat, 2019) that can provide explicit information about task performance or results (Genthe et al., 2018). Some investigators have distorted the visual feedback to induce altered movement patterns (French, Morton, Charalambous, & Reisman, 2018; Kim & Krebs, 2012; Kim, Ogilvie, Shimabukuro, Stewart, & Shin, 2015; Taylor & Ivry, 2014). From a learning perspective, distorted visual feedback may involve both implicit and explicit components (French et al., 2018; Taylor,

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Krakauer, & Ivry, 2014). That there is at least some implicit component, suggests that distorted visual feedback may facilitate the production of desired movements with or without conscious awareness (French et al., 2018). Although it has been suggested that eliciting altered gait without awareness (i.e., no instruction) may enhance retention (Kim et al., 2015), others have demonstrated that when the desired movement is created with awareness (i.e., explicit instructions), the repeated production of the desired movement is the critical component, such that storage of the new movement is accomplished through use-dependent learning (Wood, Kim, French, Reisman, & Morton, 2020).

Using a learning strategy that does not rely solely on conscious awareness also has the potential to reveal the biomechanical mechanisms underlying altered movements. Because participants are not informed *how* to modify their movement, such a strategy creates the potential for naturally emergent gait modifications. Understanding how potential biomechanical mechanisms self-organize without instruction can inform future work to emphasize the critical biomechanical features of propulsion for pathologic populations. Our overall purpose was therefore to evaluate the capacity of a goal-directed motor learning approach to manipulate propulsive forces during gait. Specifically, we sought to test the effect of distorted visual feedback of propulsive forces during treadmill walking on the capacity to alter propulsion, as well as the biomechanical mechanisms underlying any alterations in propulsion. Based on prior work using distorted visual feedback of step lengths (French et al., 2018; Kim & Krebs, 2012), we hypothesized that our young, unimpaired adults would increase their limb propulsion in response to the magnitude of the distortion. Because prior work has suggested that the peak ankle plantarflexion moment and trailing limb angle (TLA) represent two biomechanical mechanisms that can modulate propulsive force (Hsiao et al., 2015), we hypothesized that participants would naturally increase both of these metrics to enhance propulsion. Furthermore, because participants were unaware of when feedback would be distorted (Kim et al., 2015), we anticipated that participants would maintain short-term increases in propulsion upon removal of feedback. Finally, we sought to benchmark any biomechanical changes in response to distorted visual feedback relative to volitional attempts to maximally increase propulsion.

2. Methods

2.1. Participants

Twenty unimpaired individuals between the ages of 18 and 30 years were recruited for this study. All participants had normal or corrected to normal vision and were able to walk without stopping for up to 15 min. Exclusion criteria included the presence of any uncontrolled cardiorespiratory/metabolic disease, or other neurological or orthopedic disorders that may affect gait, or a history of balance deficits or unexplained falls. All participants signed an informed consent form approved by the Institutional Review Board of the University of North Carolina at Chapel Hill. Although we recruited 20 participants for testing, we removed three subject's data after testing. One participant was removed because they did not complete one of the conditions, and two were removed due to difficulty volitionally modulating propulsion prior to testing (they appeared to misunderstand propulsion for vertical force and responded by 'stomping'). Thus, we analyzed the remaining 17 participants (22.4 ± 3.1 years of age, 1.72 ± 0.07 m, 68 ± 9 kg, 11 females and 6 males).

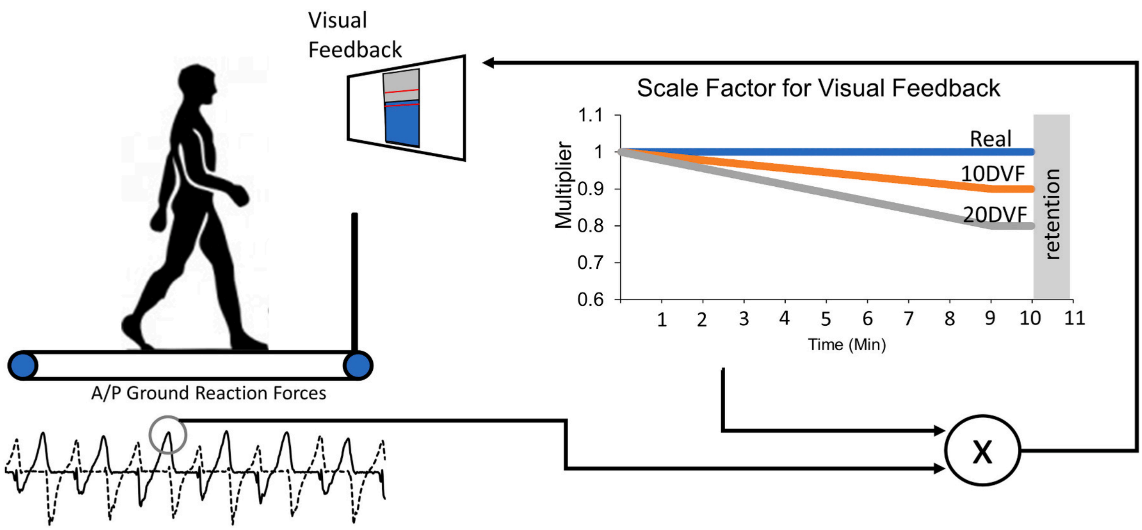

Fig. 1. Schematic illustrating study design. Participants walked on a treadmill that recorded peak propulsive forces. Peak propulsive forces were then multiplied by 1 (Real condition) or a gradually diminishing scale factor (distorted visual feedback) and presented on a bar graph for the subject immediately following each step. Subjects attempted to keep the peak propulsion (blue bar) centered between the red bounds representing one standard deviation from their mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Protocol

Each testing session began with an assessment of comfortable overground walking speed, as participants completed 2 passes across a 20-ft walkway (Zeno; ProtoKinetics, Havertown, PA). Participants had an average overground speed of 1.32 ± 0.16 m/s. All subsequent testing was performed on an instrumented dual-belt treadmill (Bertec, Worthington, OH) at the participants' comfortable walking speed (1.27 ± 0.15 m/s), although 5 subjects requested to walk slower than their overground gait speed. Participants began by walking for three minutes on the treadmill without any visual feedback (baseline). The mean and SD of the propulsive force during baseline were recorded for use in subsequent feedback conditions. Specifically, we used Labview software (National Instruments, Austin, TX) to calculate and display step-by-step feedback of peak propulsion, by projecting the data onto a screen in front of the treadmill (Fig. 1). Visual feedback of each limb's peak propulsion was displayed in the form of a bar graph that was updated with each step. The graph also contained target bounds that represented ±1 standard deviation from the mean as obtained from that participant's baseline period. Although the baseline mean (i.e., target) was not indicated to reduce the number of lines, participants were instructed "to keep your peak propulsive force centered between the two bounds" that represented the standard deviation. To aid in the interpretation of the graph, an indicator was added to display "Great Job" if the propulsive force was within a standard deviation, or "Too Much" or "Too Little" if the propulsive force went above or below the standard deviation range, respectively. The participants were given a short time to explore gait modifications that could make their propulsive force increase or decrease.

Participants then completed three randomly ordered visual feedback conditions (control, 10% distorted visual feedback, 20% distorted visual feedback). A five-minute rest was taken in between each condition. Participants were instructed to let the researcher know "if you feel like you are changing the way you walk to keep the bar centered in the bounds". During each of the randomly ordered conditions, participants walked for ten minutes while receiving feedback of their propulsive forces. The feedback was then removed for one minute as the participants continued walking, to test for short term retention. During the *Real* condition, the peak propulsive force feedback was unaltered, whereas the visual feedback of propulsive force was systematically distorted during the other two conditions. Specifically, during the 10% Distorted Visual Feedback *(10DVF)* condition, the peak of the measured propulsive force was multiplied by a gradually diminishing scale factor that decreased with each step, such that by the end of the nine-minute adjusting period, the visual feedback represented 90% of the 'real' value. The scale factor was adjusted on a step-by-step basis to ensure subtle changes over time. In the *20DVF* condition the diminishing scale factor was doubled so that the visual feedback represented 80% of the 'real' value after approximately nine minutes of walking.

After completing the three feedback conditions, participants were told that their feedback had been distorted in the 10DVF and 20DVF conditions. They were then asked to use the real feedback to perform a *Maximum* propulsion condition in which they produced as much propulsive force as possible (increase the value on the graph) for 1–2 min. We included the *Maximum* condition to compare how subjects altered their propulsive force during the distorted visual feedback, relative to their maximum capacity. Notably, the Maximum condition employed real, accurate feedback that made use of explicit learning processes.

During all conditions, we captured limb segment kinematics while walking on the treadmill using 14 mm retroreflective markers that were placed on the participants' pelvis and bilateral thighs, shanks, and feet (McCain et al., 2019). The locations of the markers were recorded in 3-dimensional space by an 8-camera motion capture system (MX40+, Vicon, Los Angeles, CA). Limb kinematics were recorded at 120 Hz and ground reaction forces from the treadmill were recorded simultaneously at 1200 Hz. Data were collected for the first 50 s of every minute for all 11 min.

2.3. Data management and analysis

We used Visual3D (C-Motion, Bethesda, MD) to calculate joint moments using inverse dynamics, based on segment mass and estimated center of mass (COM) locations derived from standard regression equations (Dempster, 1955). We then used custom Labview (National Instruments, Austin, TX) programs to compute peak propulsion (i.e., the peak of the anteriorly directed ground reaction force), the TLA at peak propulsion, peak plantarflexion moment, peak hip extension moment (early stance), peak hip flexion moment (late stance), and step length. The TLA was computed as the angle formed by a vertical line and a line connecting the pelvis COM position and the center of pressure (Lewek & Sawicki, 2019). Step length was calculated as the anteroposterior distance between heel markers at each initial contact. Each outcome measure was computed for each step and normalized to the average obtained from the initial three-minute baseline (i.e., no feedback presented). A value of 100% would therefore represent no change from baseline. Data were then averaged for each subject across minute 10 to represent late Learning and minute 11 to represent Retention. During the Maximum condition, we selected the four consecutive steps with the highest peak propulsive force for further analysis.

To assess each of the six outcome measures, we used SPSS (ver 25, IBM, Chicago, IL) to perform separate two-way repeated measures ANOVAs (repeated for condition [Real, 10DVF, 20DVF] and time [minutes 10, 11]). Significant main effects were then evaluated with paired samples *t*-tests with a Bonferroni correction to account for multiple comparisons. We calculated effect sizes (partial eta squared and Cohen's d, as appropriate) to aid in interpretation of results. We then performed Pearson correlations to assess potential associations between the change in peak propulsion (during minute 10 relative to baseline) and the changes in the suspected biomechanical determinants (i.e., changes in peak plantarflexion moment, TLA, peak hip flexion moment, peak hip extension moment, and step length) across the three conditions. Finally, we assessed the ability to increase peak propulsion maximally by comparing the Maximum condition to the Real condition using a paired samples t-test. We then assessed the contributions to this increased propulsion force using Pearson correlations between the peak propulsion force and each of the potential biomechanical moderators during the Maximum condition.

3. Results

3.1. Influence of distorted visual feedback

Participants gradually increased peak propulsion during the learning phase to an average of 109 ± 2% for the 10DVF condition and 120 ± 5% of baseline for the 20DVF condition. These values remained relatively unchanged through the retention phase (Fig. 2), resulting in a significant main effect of condition ($p < 0.001$; $\eta_p^2 = 0.868$) but no effect of time ($p = 0.452$; $\eta_p^2 = 0.036$). Specifically, by late learning (i.e., minute 10), participants were walking with substantially greater propulsion during the 10DVF condition ($p < 0.001$; d = 3.86) and the 20DVF condition ($p < 0.001$; d = 3.81) compared to the REAL condition. Furthermore, peak propulsion during the 20DVF condition was greater than peak propulsion during the 10DVF condition ($p < 0.001$; d = 2.01). These differences persisted through the retention phase (i.e., minute 11; $p < 0.001$; $\eta_p^2 = 0.690$).

With respect to joint kinetics, peak plantarflexion moment remained unaltered (interaction effect: $p = 0.689$; $\eta_p^2 = 0.015$; Fig. 3) between conditions ($p = 0.469$; $\eta_p^2 = 0.042$) and over time ($p = 0.626$; $\eta_p^2 = 0.015$). The peak hip extension moment during early stance was also unchanged (interaction: $p = 0.335$; $\eta_p^2 = 0.066$; condition: $p = 0.478$, $\eta_p^2 = 0.045$; time: $p = 0.734$, $\eta_p^2 = 0.007$; Fig. 4). We did, however, observe a difference between conditions for peak hip flexion moment ($p = 0.002$; $\eta_p^2 = 0.314$). Specifically, the 20DVF condition had lower peak hip flexion moment than the REAL condition ($p = 0.007$; d = 0.81).

Limb posture changes during late stance were observed with alterations in TLA across conditions ($p < 0.001$; $\eta_p^2 = 0.538$; Fig. 5), but no change over time ($p = 0.690$; $\eta_p^2 = 0.010$). In particular, we observed that participants increased their TLA when feedback was distorted, such that greater TLA occurred during the 10DVF compared to the REAL condition ($p = 0.023$; d = 0.72), and greater TLA was observed during the 20DVF condition compared to both 10DVF ($p = 0.004$; d = 0.94) and REAL conditions ($p < 0.001$; d = 1.18). Likewise, the participant's step length was different between conditions ($p = 0.001$; $\eta_p^2 = 0.413$), but not different over time ($p = 0.426$; $\eta_p^2 = 0.040$), with participants exhibiting longer step lengths during the 20DVF condition than during the 10DVF ($p = 0.013$; d = 0.80) and REAL conditions ($p = 0.006$; d = 0.90).

3.2. Naturally emergent determinants of propulsion

We observed a positive correlation between the change in peak propulsion and the change in TLA ($p < 0.001$; $r = 0.707$; Fig. 6) and the change in step length ($p < 0.001$; $r = 0.575$). We also noted a negative relationship between the change in peak propulsion and the change in late stance hip flexion moment ($p = 0.012$; $r = -0.348$). Finally, there was no relationship between the change in peak propulsion and any change in ankle plantarflexion moment ($p = 0.480$; $r = -0.101$).

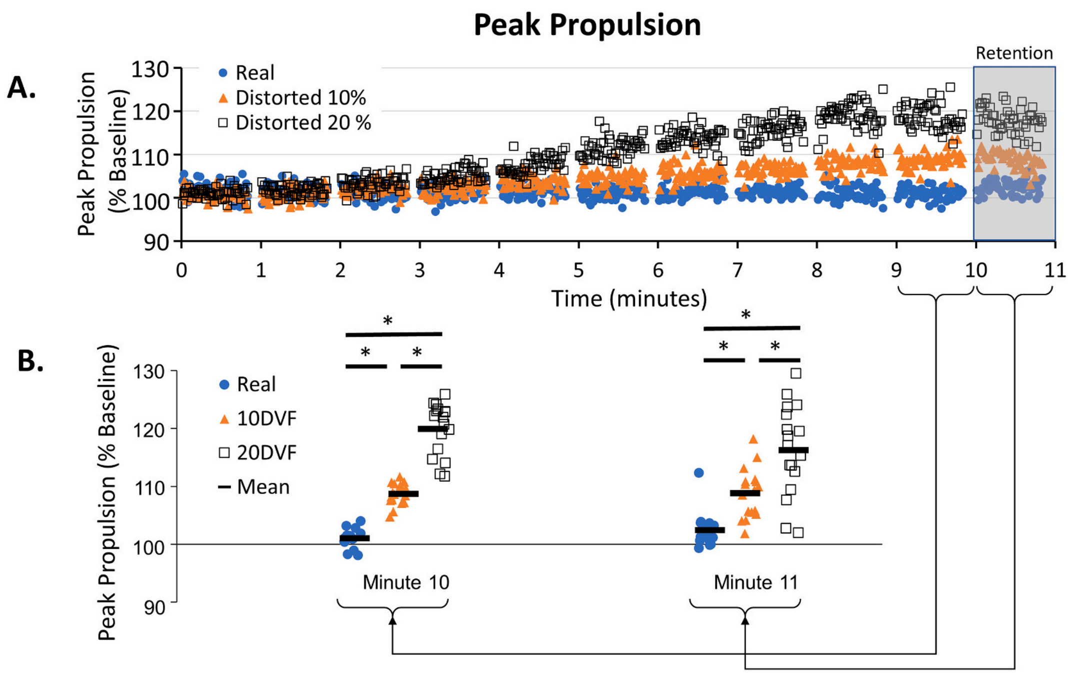

Fig. 2. A) Ensemble group mean of peak propulsion on a step by step basis for the Real, 10DVF, and 20DVF conditions. B) The peak propulsion was averaged for minutes 10 (late learning), and 11 (retention) for each subject. A significant main effect of condition was noted. * indicates significant difference ($p < 0.05$) between conditions.

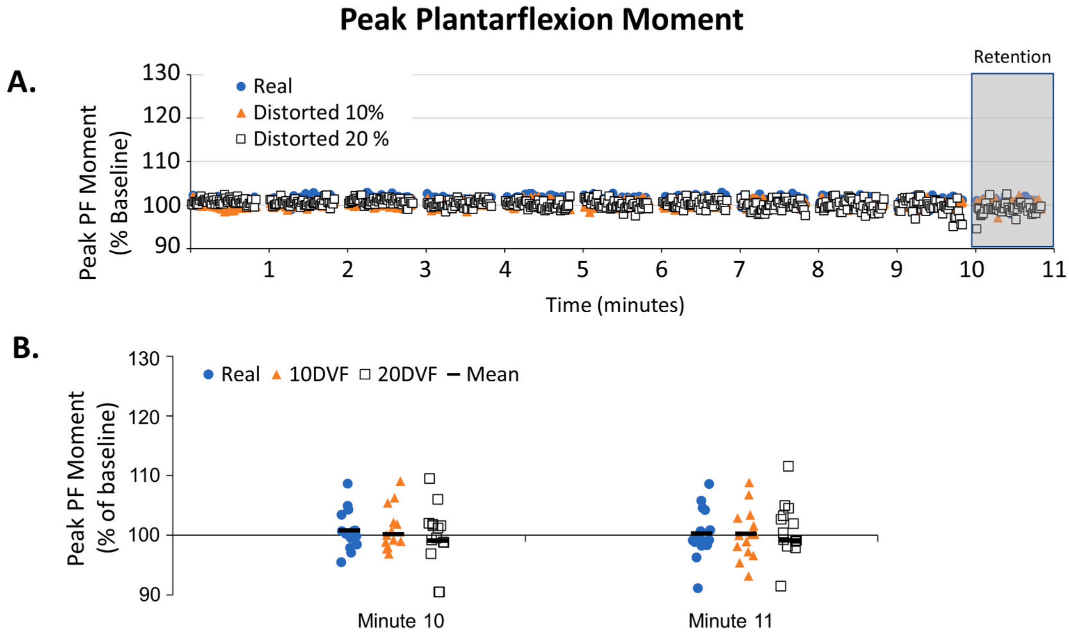

Fig. 3. A) Ensemble group mean of peak plantarflexion moment on a step by step basis for the Real, 10DVF, and 20DVF conditions. B) The peak plantarflexion moment was averaged for minutes 10 (late learning), and 11 (retention) for each subject, although no changes were observed.

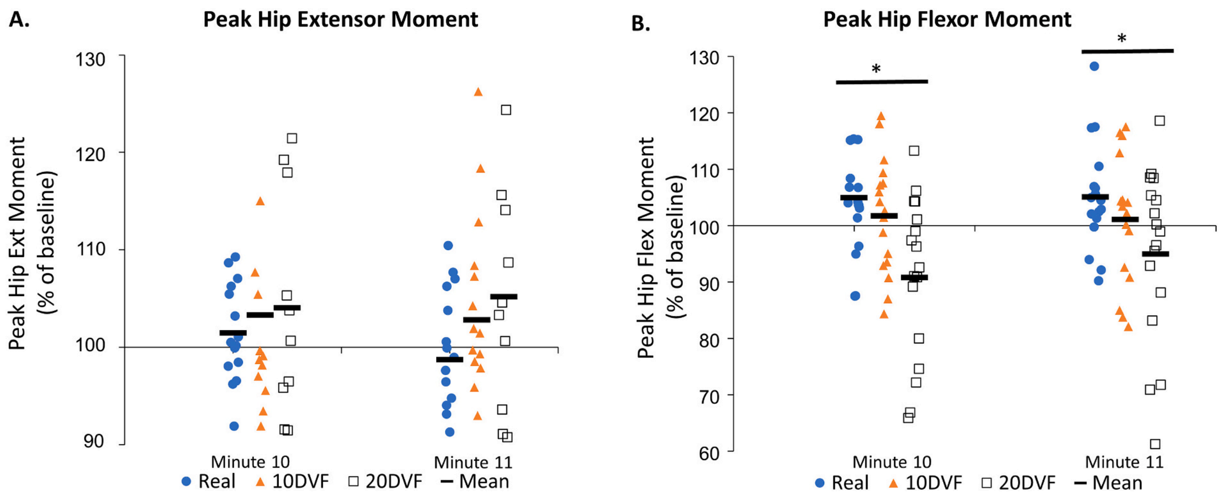

Fig. 4. A) The peak hip extensor moment during early stance was averaged over minutes 10 and 11 for each subject. B) The peak hip flexor moment during late stance was averaged for minutes 10 and 11 for each subject. Here, a significant reduction in peak hip flexor moment was noted during the 20DVF condition.

3.3. Changes relative to maximum volitional propulsion

When asked to produce maximum propulsive force, participants were able to produce 145 ± 31% of baseline propulsion ($p < 0.001$; d = 1.45). This was accompanied by a concomitant increase in the hip extension moment during early stance ($p = 0.005$; d = 0.78), trailing limb angle (p < 0.001; d = 1.51) and step length ($p = 0.003$; d = 0.87) and a decrease in hip flexion moment during late stance (p < 0.001; d = 1.16). However, no change in plantarflexion moment was observed during maximum propulsion ($p = 0.419$; d = 0.20). The increase in peak propulsion was positively related to the increased TLA ($p = 0.002$; $r = 0.707$) and increased step length ($p = 0.004$; $r = 0.664$). Despite no increase in plantarflexion moment, we did observe an association between the increased peak propulsion and the change in plantarflexion moment (p < 0.001; $r = 0.772$).

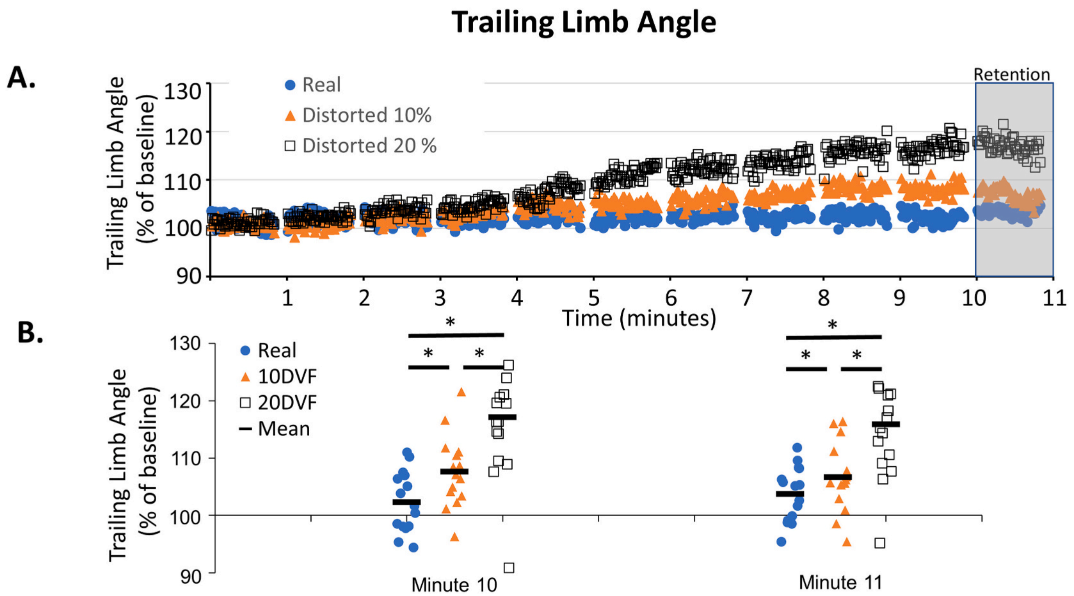

Fig. 5. A) Ensemble group mean of trailing limb angle on a step by step basis for the Real, 10DVF, and 20DVF conditions. B) The trailing limb angle was averaged for minutes 10 (late learning) and 11 (retention) for each subject. A significant main effect of condition was noted. * indicates significant difference ($p < 0.05$) between conditions.

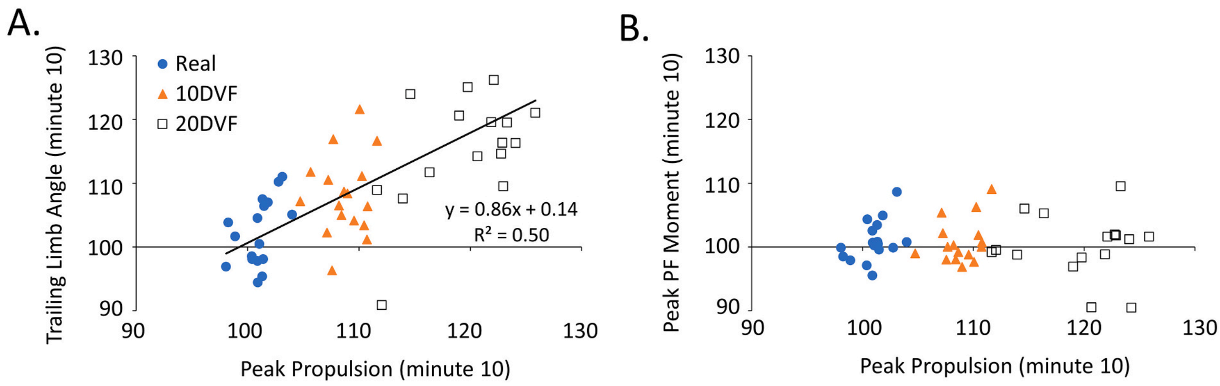

Fig. 6. A) The change in trailing limb angle was significantly related to the change in peak propulsion ($p < 0.001$; $r = 0.71$), although B) there was no relationship between the change in peak plantarflexion moment and peak propulsion.

4. Discussion

Our hypothesis that distorted visual feedback would induce young, unimpaired adults to increase their limb propulsion was supported by these data. Even without instructions regarding the visual distortion, we observed that participants increased their limb propulsion proportionately in response to the distorted visual feedback. However, whereas the increase in TLA was related to the increase in propulsive forces, the plantarflexion moment remained unaltered, leading us to partially reject our second hypothesis. Additionally, we observed that participants maintained their peak propulsive forces from the late learning phase and into the retention phase. Interestingly, participants used similar, but not identical biomechanical strategies in responding to the distorted visual feedback compared to explicitly producing maximum propulsion. We believe that these data will be helpful for eliciting increased propulsion in populations that typically exhibit reduced propulsion during habitual walking.

Participants increased their peak propulsion proportionally for the distorted visual feedback provided. In fact, by the end of the late learning phase, participants had increased peak propulsion by an average of 9 ± 2% in the 10DVF condition and 20 ± 5% during the 20DVF condition. When the feedback was removed (i.e., minute 11) participants maintained their magnitude of peak propulsion. Because participants were unaware that the feedback was distorted, we take this finding to suggest that implicit processes were at least partially involved (Kim et al., 2015). Of course, participants were told what parameter was being displayed as visual feedback, suggesting that there was also some explicit knowledge of the task requirements. Our choice to only display the peak propulsion force from each step, rather than the entire braking/propulsion curve, suggests that we may have somewhat biased our subjects towards greater explicit learning (Taylor et al., 2014). Nevertheless, the fact that participants were not given instructions during the one-minute retention period, yet they maintained the increase in propulsive force, suggests that both implicit and explicit components to learning were involved (Kim et al., 2015; Taylor et al., 2014).

There were several notable differences between our use of distorted visual feedback and that of others. First, our feedback promoted the continuation of symmetric gait patterns by distorting both legs similarly. In contrast, others have attempted to create asymmetric patterns (largely of step length) by either altering feedback of just one limb (Kim et al., 2015; Kim & Krebs, 2012) or both limbs (French et al., 2018; Hussain, Hanson, Tseng, & Morton, 2013; Wood et al., 2020). This distinction is important because when the feedback is removed, large magnitudes of gait asymmetry are perceptible (Wutzke, Faldowski, & Lewek, 2015) and thus participants in those asymmetric cases may be more likely to restore symmetric gait upon removal of the feedback. We believe that by altering both limbs (i.e., maintaining symmetry), and inducing only small increases in propulsion force (i.e., less than half of reserve) that the altered gait pattern in our participants remained subconscious such that they were more likely to continue the increased propulsion when the feedback was removed. The second major difference in our use of distorted visual feedback is in the use of instructions. Whereas some investigators have provided explicit instructions about how the feedback would change (Wood et al., 2020), we opted to withhold this information, such that participants were blinded to the feedback. Although French and colleagues noted that the provision of instructions did not influence retention (French et al., 2018), the production of asymmetric gait may also have contributed to this finding.

We were particularly interested in the naturally emergent biomechanical strategies that participants might use to increase peak propulsion. Prior work by Hsiao and colleagues stressed the dual importance of the TLA and the peak ankle plantarflexion moment (Hsiao et al., 2015). Those authors suggested that changing TLA may contribute twice as much to increase propulsive force as changing plantarflexion moment (Hsiao et al., 2015), with participants perhaps choosing to increase TLA because it is metabolically more cost efficient than increasing plantarflexion moment (McCain et al., 2019). Despite the potential role that both TLA and ankle plantarflexion moment play in modulating propulsion, our data suggest that TLA was the primary biomechanical mechanism through which our unimpaired participants increased their limb propulsion. Although, we anticipated that the plantarflexion moment would increase with greater propulsion, our findings are consistent with others who have used explicit feedback to modulate propulsion (Browne & Franz, 2018). Given that there were no gait abnormalities in our participants, it is likely that the subjects plantarflexion moment was already adequate. Instead, the increase in TLA allowed them to make better use of this already adequate plantarflexion moment (Lewek & Sawicki, 2019). Interestingly, when participants were required to increase propulsion to maximum, it appeared that the plantarflexion moment becomes more important. Although there was no increase in the plantarflexion moment for the maximum condition, those who increased their plantarflexion moment produced greater propulsion as a result. At the relatively low levels that we tested with the distorted visual feedback; however, it appears that participants were capable of modulating propulsion easily through TLA without altering the plantarflexor moment. The increase in TLA also appeared to emerge as an increase in step length, as comparable findings were apparent in both measures.

The change in peak propulsion due to distorted visual feedback was associated with altered hip joint moments. There is a well-known distal to proximal redistribution of joint moments in older adults (DeVita & Hortobagyi, 2000) and individuals post-stroke (Nadeau, Gravel, Arsenault, & Bourbonnais, 1999) to retain forward progression. For example, higher hip extension moments during early stance are a common compensation for reduced plantarflexion moments in older adults (Browne & Franz, 2019; DeVita & Hortobagyi, 2000). Alternatively, Nadeau and colleagues observed that individuals following stroke tended to increase the hip flexion moment to compensate for weakness in their plantarflexor muscles (Nadeau et al., 1999). This compensation is particularly helpful for swing limb advancement. Although we did not observe a change in the hip extension moment, we did note that late stance hip flexion moments decreased with greater limb propulsion. We propose that hip flexion moments decreased because the increased TLA created a more effective use of the existing plantarflexion moment to increase propulsion (Lewek & Sawicki, 2019). However, this strategy of increasing TLA to augment propulsion without increasing ankle moments is likely only possible in the presence of adequate plantarflexion moments. For instance, Jonkers et al. noted that higher functioning individuals post-stroke modulated their speed by increasing ankle plantarflexion and hip flexion moments, whereas lower functioning individuals do not (Jonkers, Delp, & Patten, 2009). Thus, because our participants had ample habitual plantarflexion moments, they could simply modulate propulsion via an alteration in TLA.

We were curious if participants would use different biomechanical mechanisms to alter propulsion when asked explicitly to produce maximum propulsion compared to the more subtle and combined implicit/explicit propulsive changes in the 10DVF and 20DVF conditions. Interestingly, the importance of ankle plantarflexion moments became apparent during the Maximum condition, which was not observed during distorted visual feedback. Notably, we observed the presence of a relationship between the peak plantarflexion moment and peak propulsion only during the maximum condition. We suspect that the lack of a presence of this relationship during the DVF conditions is due to the fact that our young, unimpaired participants were only producing a relatively small percentage of their maximum propulsive force during the distorted visual feedback conditions, tapping into less than half of their reserve (i.e., 20% vs 45%). In that case, increasing the TLA may represent a more efficient and cost-effective strategy to increase limb propulsion compared to increasing plantarflexor moment. However, once participants were asked to produce their maximum propulsive force, this strategy was no longer sufficient; those who increased the plantarflexion moment were then capable of further increasing propulsion. Thus, we propose that increasing the plantarflexion moment becomes necessary only when exceeding a certain limb propulsion threshold is required. For example, walking uphill, faster walking, and accelerating all require greater propulsion than habitual walking, and has important implications for older adults, individuals post-stroke, and others with propulsion deficits. In particular, if older adults or individuals post-stroke have a smaller capacity to increase their TLA, possibly because of less flexibility in their hip flexors (Kerrigan, Xenopoulos-Oddsson, Sullivan, Lelas, & Riley, 2003), they would require an increase in their ankle plantarflexion moment to increase limb propulsion at a lower threshold value. Unfortunately, ankle plantarflexion deficits are common in both populations (Chen & Patten, 2008; DeVita & Hortobagyi, 2000), and an increase in plantarflexion moments may not always be possible (Nadeau et al., 1999), or help with increasing propulsion (Lewek, Raiti, & Doty, 2018).

4.1. Limitations

There are several limitations associated with this work. First, the visual feedback provided to participants only displayed a range (i.e., one standard deviation of baseline) and did not explicitly indicate the mean of the baseline. Even though participants were instructed to maintain the visual bar near the center of these bounds, they could still be within the bounds and performing a "good job" while not achieving our intended target. Second, we do not know if the learning paradigm successfully alters propulsive forces in other environments (e.g., off the treadmill) or whether there were any long-term effects. Future studies will be needed to answer these questions with appropriate transfer and retention testing. Finally, although participants were aware that the feedback may be distorted during some conditions, they were blinded to all conditions (except for the maximum condition). Therefore, we cannot be sure of the true extent of implicit and explicit learning attained during testing. Perhaps the inclusion of an additional control condition, in which participants were given visual guidance and explicit instructions to gradually increase limb propulsion during the training period, would have helped clarify the extent of implicit vs explicit learning.

5. Conclusions

In summary, our findings suggest that peak propulsion can be modified using distorted visual feedback. The dominant biomechanical mechanism driving the altered propulsion appears to be an increase in the trailing limb angle. Our future work will extend this paradigm to those with deficits in peak propulsion, including unimpaired older adults as well as those with chronic hemiparesis post-stroke.

Declarations of interest

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