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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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Hemiparesis following stroke results in debilitating motor impairments including decreased walking ability. Reduced paretic leg propulsion, measured as the anterior component of the ground reaction force (AGRF), is a common gait deficit that negatively impacts walking ability in post-stroke individuals. Gait interventions that target AGRF often result in improvements to walking speed and function. Real-time biofeedback is a promising post-stroke gait rehabilitation strategy that can provide real-time physiological information to users during training. Our previous study in a post-stroke population show that real-time AGRF biofeedback training results in significant improvements in paretic leg propulsion without inducing compensatory changes in the non-paretic leg.

However, several questions regarding the use of real-time biofeedback remain. To date, no studies have compared AGRF biofeedback training with other gait interventions that target propulsion. Moreover, other biomechanical variables that may contribute to improved walking function have yet to be delivered via real-time biofeedback. The experiments presented in this thesis explore these gaps in research in an able-bodied population. In our first experiment, we compare the walking outcomes of able-bodied individuals following exposure to verbal feedback and real-time biofeedback. Our results demonstrate the efficacy and engagement of real-time biofeedback in improving gait propulsive forces, strengthening its promise as a viable post-stroke gait intervention. In our second experiment, we investigate, for the first time, the effects of trailing limb angle (TLA) biofeedback on modulating gait propulsive forces and biomechanical variables. Our results provide a rationale for further investigation into the use of real-time TLA biofeedback in a post-stroke population.

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1. INTRODUCTION

Stroke is a leading cause of long-term adult disability in the United States [1]. Stroke causes damage to the neural circuits in the central nervous system [2], and can result in several neurological impairments including cognitive decline, communication disorders, and hemiparesis [3]. Hemiparesis, characterized by muscle weakness on one side of the body, is one of the most common impairments following stroke, and contributes significantly to decreased walking ability [4,5]. Because walking ability and function are highly correlated with community participation and quality of life [6-8], clinicians consider the restoration of gait a major goal of rehabilitation [9,10].

Following discharge from hospital, 60-75% of stroke survivors are capable of walking unaided [11]. However, even after discharge from rehabilitation, stroke survivors continue to experience reduced walking ability, speed, and endurance due to muscular weakness and several biomechanical deficits in the paretic leg [12-14]. Diminished strength in the hip flexors and plantar flexors contribute to impaired swing initiation and slower walking speed [15,16]. Biomechanical gait impairments such as reduced knee and ankle flexion during swing phase increases the risk for falls [2,12]. Paretic limb deficits may lead to compensatory walking strategies, such as limb circumduction and pelvic hiking, that ultimately increase energy expenditure and limit long-distance walking function [2,17-19].

While there is consensus that stroke survivors benefit from gait rehabilitation [20-28], agreement is lacking on which specific gait retraining interventions are the most efficacious [29-34]. One challenge to determining efficacy of a treatment strategy is the identification of appropriate outcome measures to evaluate improvement. Improvements to gait performance following intervention may be attributed to a variety of factors, ranging from biomechanical and muscular improvements in the paretic limb to strengthening compensatory strategies in the non-paretic limb [35]. Clinical outcome measures commonly used to assess walking performance following rehabilitation are unable to differentiate between the true restoration of gait deficits in the paretic leg and the development of compensatory strategies that rely on the non-paretic leg [36]. For example, walking speed has been, and still is, a widely used clinical measure of gross gait performance because of its simplicity, reliability, and specificity [37]. However, gait interventions that focus exclusively on improving walking speed carry the risk of encouraging compensatory mechanisms in the nonparetic limb rather than enhancing functioning of the paretic limb [38]. Therefore, there is a need for gait rehabilitation strategies that target specific gait deficits in the paretic limb while preventing the development of compensatory mechanisms in the nonparetic limb to ultimately improve walking quality and gait function [39].

Recently, paretic propulsion, defined as the anterior component of the ground reaction force (AGRF) (Figure 1), has been identified as an important gait deficit to address in post-stroke patients. Paretic AGRF is related with hemiparetic severity, gait speed, gait function, and metabolic cost [35,40-44]. Post-stroke individuals demonstrate significantly reduced AGRF in the paretic limb, and this quantitative measure of propulsion is strongly associated with hemiparetic severity as well as walking speed [40]. Bowden et al. previously demonstrated that following a 12-week gait intervention, improvements to paretic AGRF were associated with improvements in walking speed, and more importantly, paretic AGRF could be modified through rehabilitation strategies [35]. Furthermore, addressing AGRF deficits in the paretic limb may also induce improvements in other biomechanical variables that improve walking outcome. For example, Balasubramanian et al. demonstrated a clear relationship between step length asymmetry and paretic AGRF production, suggesting that improvements in AGRF production of the paretic limb may improve step length symmetry and contribute to better balance and walking ability [41].

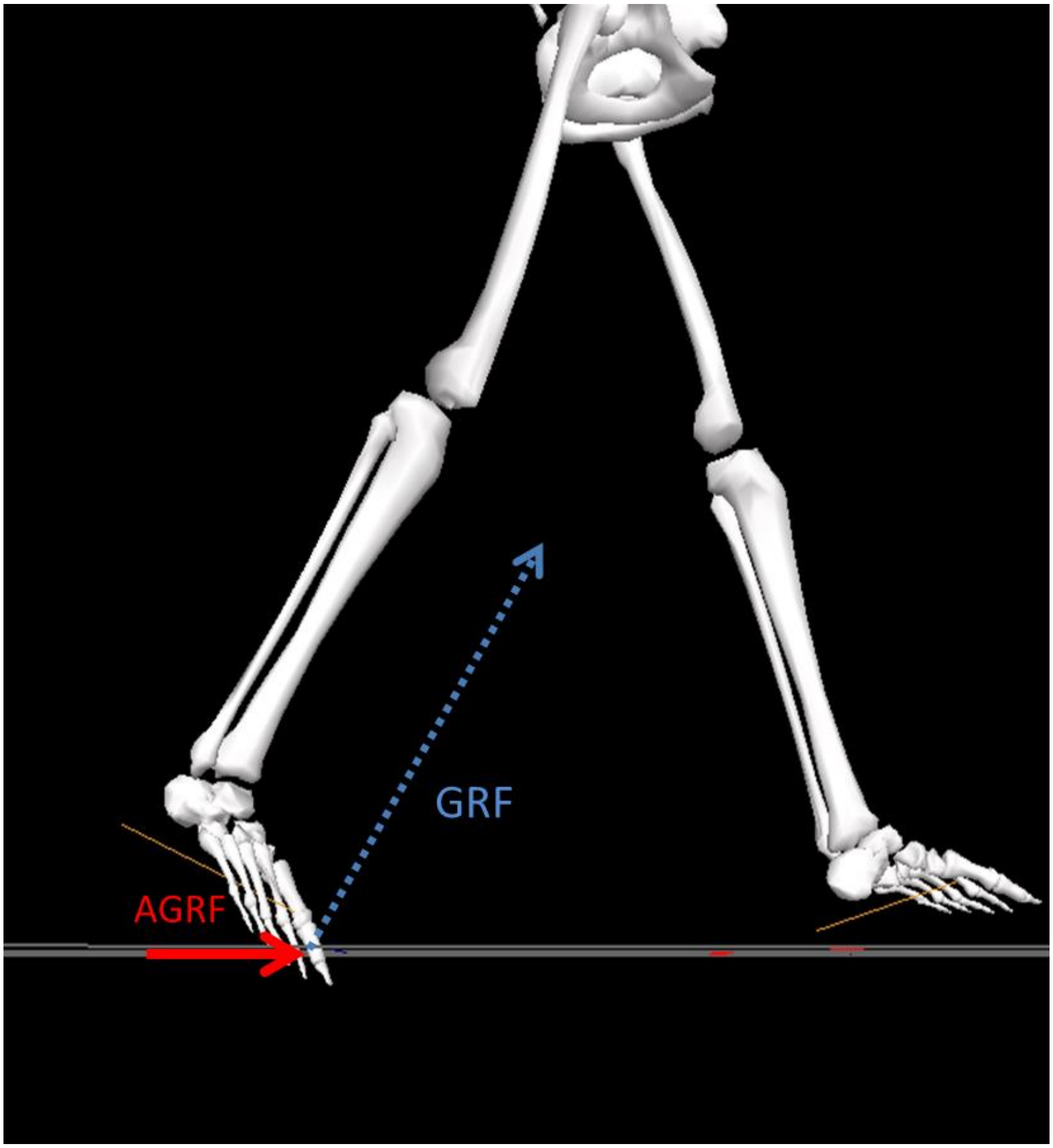

Figure 1. Anterior component of the ground reaction force (AGRF). Highlighted in red, AGRF is the anteriorly directed component of the ground reaction force (GRF).

Reduced trailing limb angle (TLA) is another important gait deficit in the post-stroke population given its relationship with AGRF and walking function [42,43,45,46]. Defined as the angle between the laboratory's vertical axis and a line joining the limb's greater trochanter and fifth metatarsal head (Figure 2), TLA serves as a measure of overall limb orientation at terminal stance. TLA also determines the proportion of ground reaction force distributed anteriorly, therefore serving as an important strategy to increase AGRF [43,46]. Targeting TLA deficits is especially important in the post-stroke population, given that post-stroke individuals are observed to preferentially increase TLA more than other biomechanical variables, such as ankle moment, to increase propulsion [45]. Hsiao et al. observed that after 12 weeks of gait training in forty-five hemiparetic stroke participants, increases in TLA contributed significantly to the increases in AGRF [47]. Moreover, TLA is likely related to other biomechanical gait variables that can contribute to improved walking outcome. For example, increases in TLA of the paretic leg may contribute to better step length symmetry [42], which is associated with improvements in energy expenditure and balance [48].

Real-time biofeedback is a promising post-stroke gait retraining strategy that targets specific biomechanical impairments, including AGRF and TLA. Biofeedback is a method of providing users with real-time physiological information that would otherwise remain unknown. During gait rehabilitation, biofeedback training can deliver information regarding specific gait deficits, enhancing awareness of deficits during training and allowing for self-correction of aberrant gait patterns [49]. Previous studies investigating biofeedback have demonstrated that step length biofeedback induced improvements in step length symmetry in post-stroke individuals [50,51]. Franz et al. demonstrated that older adults increase both AGRF and walking speed after a single session of biofeedback training [52]. More recently, our lab demonstrated that in response to

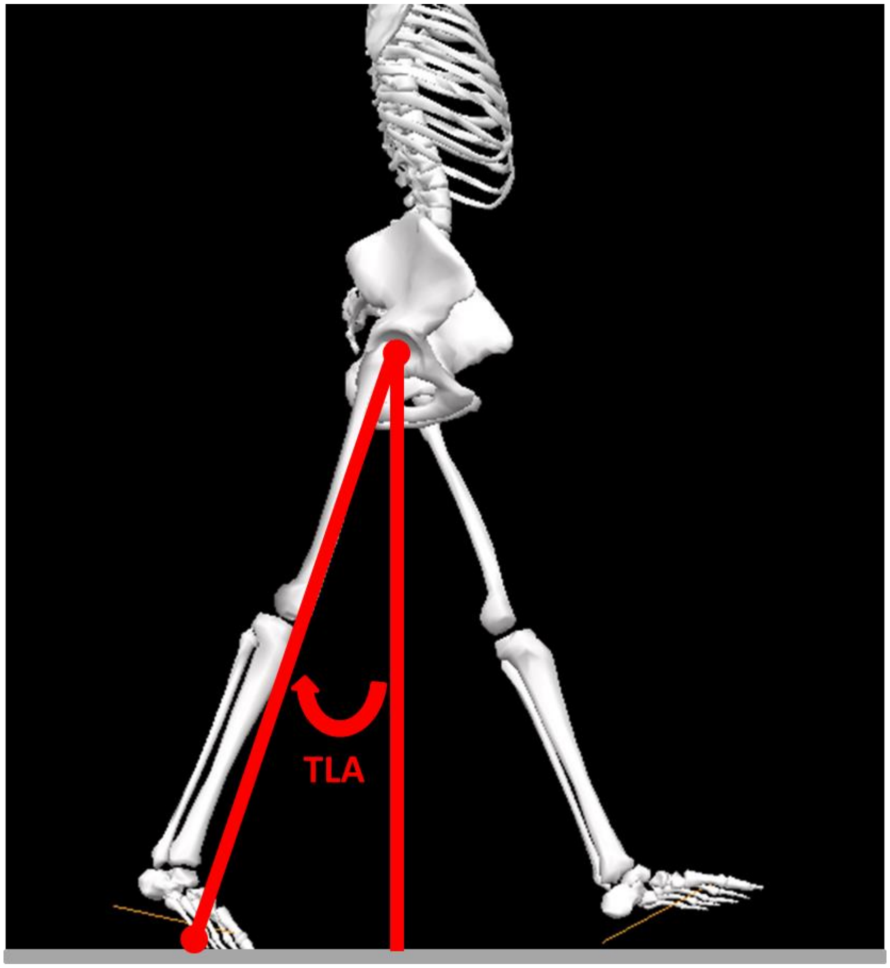

Figure 2. Trailing limb angle (TLA). TLA is defined as the angle between the laboratory's vertical axis and a line connecting the greater trochanter and fifth metatarsal head marker.

real-time audiovisual AGRF biofeedback, both able-bodied and stroke individuals can increase AGRF unilaterally for the targeted/paretic limb, without changes to AGRF in the non-targeted/nonparetic limb. [53,54]. Thus, biofeedback serves as an effective gait retraining tool that can target specific deficits of the paretic limb without inducing compensatory changes in the nonparetic limb.

Several questions remain regarding use of real-time biofeedback for gait rehabilitation. First, the use of real-time biofeedback requires an intricate lab set-up containing expensive motion capture systems and complex hardware. Verbal feedback, on the other hand, is a tool available to every rehabilitation clinician and requires no additional set-up or cost. Previous studies have established that able-bodied individuals can increase their push-off forces by ~27% in response to verbal instruction to walk with greater ankle push-off [55-57]. With barriers to cost and access, it is important to justify the use of biofeedback in rehabilitative settings and establish whether real-time instrumented biofeedback training is superior to verbal feedback training at improving walking ability. Therefore, the first aim of this thesis is to investigate and compare the effects of verbal feedback and real-time biofeedback on AGRF production.

Second, biofeedback training can provide information regarding several different gait variables. However, there remain some important biomechanical variables that have yet to be targeted during biofeedback training. While previous studies have demonstrated the benefits of step length and AGRF biofeedback on walking function [50-52], no studies have investigated the effects of TLA biofeedback on walking ability. Thus, the second aim of this thesis is to explore the immediate effects of TLA biofeedback on propulsive forces and biomechanical variables. More specifically, the study will compare the effects of AGRF biofeedback and TLA biofeedback on peak AGRF production and peak TLA.

2. COMPARING THE EFFECTS OF VERBAL FEEDBACK AND REAL-TIME BIOFEEDBACK ON GAIT PROPULSIVE FORCES

Real-time biofeedback is a useful gait rehabilitation tool that can target specific gait impairments in post-stroke individuals. Previous studies have noted the benefits of step length and AGRF biofeedback on walking function [50-52]. Moreover, our previous work shows increases in gait propulsive forces in the targeted/paretic limb of able-bodied and post-stroke individuals after a single session of real-time AGRF biofeedback training [53,54].

In addition to targeting specific gait deficits, biofeedback may also increase patient motivation and engagement during training. Real-time biofeedback can provide users with tangible and specific goals during training, allowing them to monitor their own success and progression. With repeated successes, participants may enjoy a greater level of motivation. Interventions that increase patient engagement, motivation, and salience during training may enhance neuroplasticity and motor learning [58,59].

However, real-time biofeedback training that targets biomechanical variables in gait requires the use of expensive motion-capture cameras and complicated lab equipment. Alternatively, verbal feedback is a tool available to every clinician at no additional cost. Previous studies have established that able-bodied individuals can increase their push-off forces by ~27% in response to verbal instruction to walk with greater ankle push-off [55-57].

Thus, it is important to justify the use of real-time biofeedback targeting biomechanical gait variables during training given the barriers to cost and access. This study compares the effects of verbal feedback and real-time AGRF biofeedback on AGRF production in able-bodied individuals. Furthermore, this study will measure and compare the engagement level of participants during verbal feedback training and real-time biofeedback training. We hypothesize that compared to verbal feedback, the use of real-time biofeedback will result in greater increases of AGRF production, as well as greater engagement levels.

Methods

Seven neurologically unimpaired individuals (age = 25±3.1 years, 2 females) participated in one session of treadmill walking at a self-selected speed. Participants were excluded if they had a musculoskeletal or neurological disorder affecting gait. All participants provided informed consent and the study was approved by the Institutional Human Subjects Review Board.

Marker setup and determination of self-selected speed

Reflective markers were attached to the trunk, pelvis, and bilateral thigh, shank, and foot segments. Marker position data were recorded using a 7-camera motion capture system (Vicon Inc., Colorado, USA). Participants walked on a dual-belt treadmill equipped with force platforms (Bertec Corporation, Ohio, USA), with one foot on each belt to allow for collection of ground reaction force data from each leg. For safety, participants were allowed to use a handrail located at the front of the treadmill. Participants were instructed to keep a light fingertip touch on the handrail during all walking trials. At the beginning of the session, the self-selected speed of the participant was determined by incrementally increasing the treadmill speed by 0.1 m/s until participants reported a comfortable walking speed. All subsequent gait trials were performed at this self-selected speed.

Control trial and determination of AGRF biofeedback target

Participants completed a 60-sec control trial of normal walking (without specific instruction). Baseline AGRF values were collected from this 60-sec control trial. The AGRF targets used for real-time biofeedback trials were calculated as 25% greater than baseline AGRF for the right (targeted) leg.

Methodology for verbal feedback trial

Participants completed a 60-sec walking trial in which they were verbally instructed to increase AGRF in their right leg only. Prior to beginning the trial, all participants received a scripted explanation of AGRF and were presented with the same picture depicting the direction of push-off required to increase AGRF (see appendix). At 20-second intervals during the 1-minute trial, participants were verbally reminded to “Push back harder in the ground” (Figure 3).

Methodology for instrumented real-time AGRF biofeedback trial

Participants completed a 60-sec trial using real-time AGRF biofeedback provided for their right leg only. Visual and auditory components of biofeedback were provided using a screen placed in front of a treadmill and speaker (Figure 4). The visual component of biofeedback consisted of a horizontal line with a cursor (X) that represented the current AGRF for the right leg only (MotionMonitor, Illinois, USA). The audio component of biofeedback consisted of an audible beep when the cursor entered the biofeedback target range during each gait cycle, signaling success. The targeted range was represented by a green line with a 5-Newton error-tolerance. Before the trial, participants were given instruction to push back hard enough to bring the cursor into their target AGRF range.

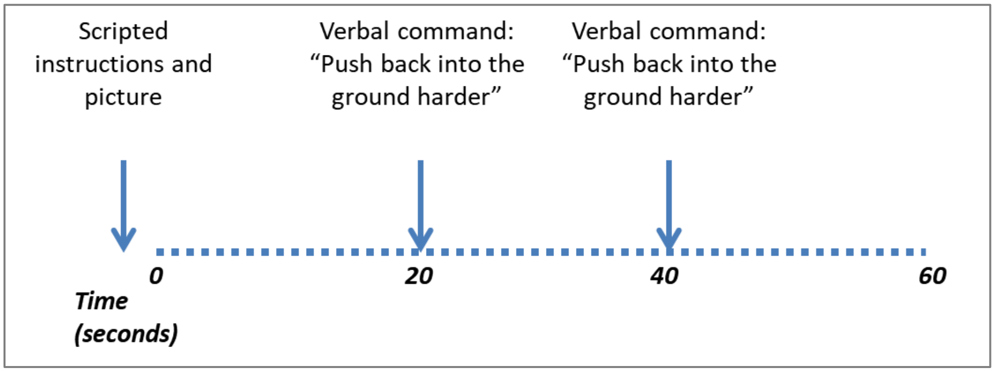

Figure 3. Schematic showing the verbal feedback trial. Prior to the start of the trial, participants received identical, scripted explanations of AGRF, and were instructed to increase AGRF in their right leg only for the entire trial. At 20 second intervals, participants received verbal reminders to "push back into the ground harder."

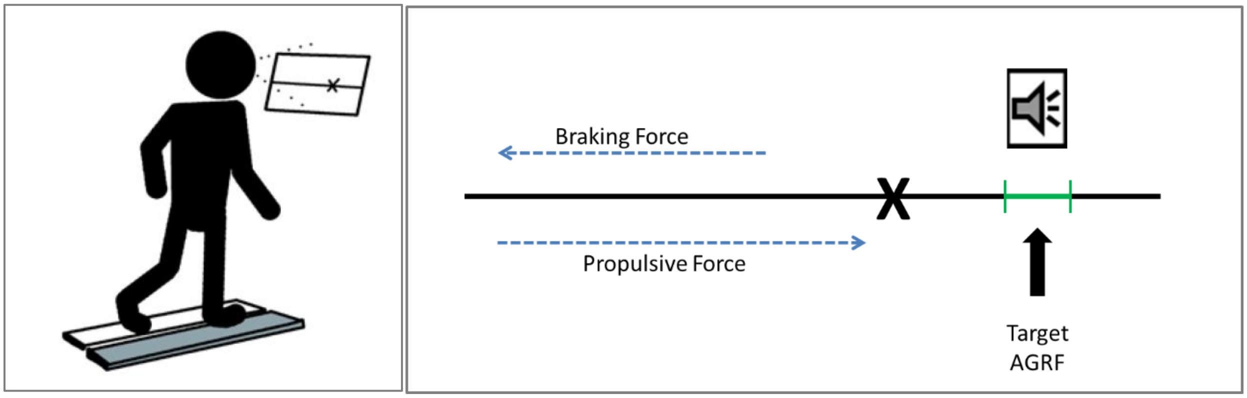

Figure 4. Schematic showing the biofeedback interface. Participants walked on a treadmill with audio and visual biofeedback provided for their right leg only. The “X” symbol represents the current AGRF generated in the right leg during the stride cycle, and the green field goal represents the target AGRF set for the right leg. An auditory tone is produced when the “X” reaches or surpasses the green field goal, indicating successful achievement of the target AGRF during the step cycle. Adapted from Schenck and Kesar, 2017.

Engagement Rating

Upon completion of each 60-sec trial (verbal feedback, real-time biofeedback), participants were asked to self-report their level of engagement during the walking trials. The engagement rating was on a scale from 1-10, with 1 being the least engaged, and 10 being the most engaged during the 60-sec trial.

Dependent Variables and Data Analysis

Primary Dependent Variables

The primary dependent variables for comparing baseline, verbal feedback, and real-time biofeedback trials were peak AGRF of the right (targeted) leg, stride-to-stride coefficient of variation (CV) of peak AGRF in the right leg, and level of engagement. Secondary variables included peak AGRF of the left (non-targeted) leg. The peak AGRF was calculated as the peak value of the anteriorly directed ground reaction forces during the terminal double support phase of the leg. The CV of peak AGRF was calculated as the stride-to-stride standard deviation from all gait cycles divided by the mean for each 60-sec trial (control, verbal feedback, real-time biofeedback).

Statistical analyses

A 1-way repeated measures ANOVA was conducted to evaluate the effect of type of feedback provided (baseline, verbal, real-time biofeedback) on each dependent variable. If the ANOVA showed a main effect, planned, paired t-tests with Bonferroni correction were conducted to compare baseline (control) data with each feedback condition (verbal feedback, real-time biofeedback). Additionally, paired t-tests with Bonferroni correction were performed to compare the dependent variables between the verbal feedback and real-time biofeedback conditions. Descriptive statistics were used to compare the engagement rating between verbal feedback and biofeedback trials. Significance level was set at $\alpha \leq 0.05$ for all tests.

Results

Peak AGRF of the right (targeted) leg

The 1-way repeated measures ANOVA showed a significant main effect of type of feedback provided on peak AGRF of the right leg ($p<0.001$, $F=44.464$) (Figure 5). The paired t-test evaluating peak AGRF of the right leg showed a significant difference between baseline and verbal feedback ($p<0.001$) and real-time biofeedback ($p=0.001$). There was no significant difference in peak AGRF of the right leg between verbal feedback and real-time biofeedback conditions ($p=1.000$).

Peak AGRF of the left (non-targeted) leg

There was no main effect of type of biofeedback provided on peak AGRF of the left leg ($p>0.5$, $F=0.625$) (Figure 5).

Stride-to-stride CV of peak AGRF of the right leg

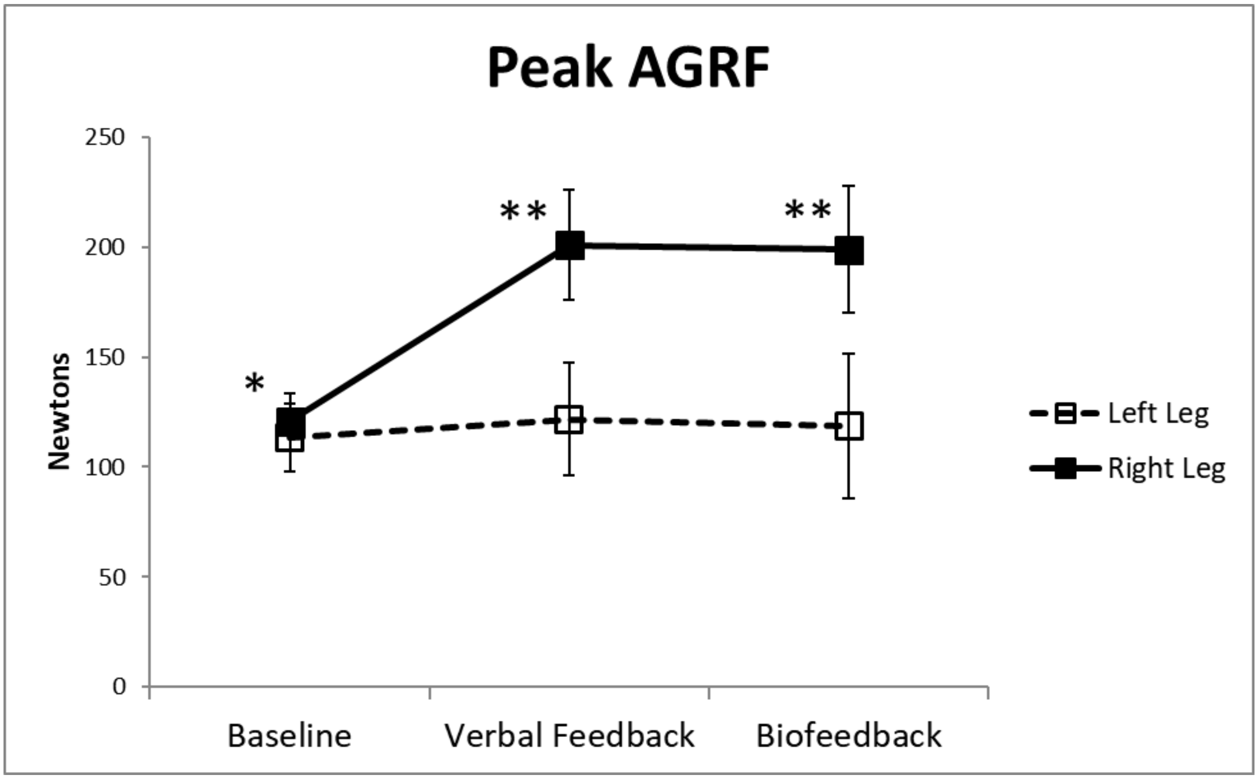

Figure 5. Peak AGRF (N=7) for the right (targeted) and left (non-targeted) legs for baseline, verbal feedback, and real-time biofeedback trials. The * symbol to the left of a metric indicates a significant main effect detected by the 1-way repeated measures ANOVA. The 1-way repeated measures ANOVA showed a significant main effect of trial condition for right leg AGRF. No significant main effect of trial condition was observed for left leg AGRF. The ** symbol indicates a significant difference in peak AGRF from the baseline condition (detected by pairwise comparisons). Pairwise comparisons showed significant increases in right leg AGRF compared to baseline in the verbal feedback and biofeedback trials. No significant differences in right leg AGRF were observed between the verbal feedback and biofeedback trials.

The 1-way repeated measures ANOVA showed a significant main effect of type of biofeedback provided on stride-to-stride CV of peak AGRF of the right leg (p=0.023, F=5.243) (Figure 6). When corrected for multiple comparisons, pairwise comparisons revealed a trend towards a difference in the CV of right leg peak AGRF between baseline and real-time biofeedback (p=0.098). No significant differences in CV of right leg peak AGRF were observed between baseline and verbal feedback (p>0.2) and verbal and real-time biofeedback (p>0.7).

Engagement Rating

The mean self-reported engagement ratings for verbal feedback and real-time biofeedback were 4.9 and 7 out of 10, respectively (Table 1).

Discussion

This study investigated and compared the effects of verbal feedback and instrumented real-time biofeedback on gait propulsive forces in able-bodied individuals. During a brief 60-sec exposure to real-time AGRF biofeedback, able-bodied individuals showed significant increases in their right (targeted) leg AGRF compared to baseline. There were no differences in left (non-targeted) leg AGRF production between the real-time biofeedback trial and baseline. Similarly, we show that in response to a brief 60-sec exposure to verbal feedback, able-bodied individuals increased right leg peak AGRF production compared to baseline trials. Furthermore, there were no concomitant increases in left leg peak AGRF during the verbal feedback trial.

To our surprise, there were no differences in push-off force generation when participants received qualitative, verbal feedback compared to when they received quantitative, real-time

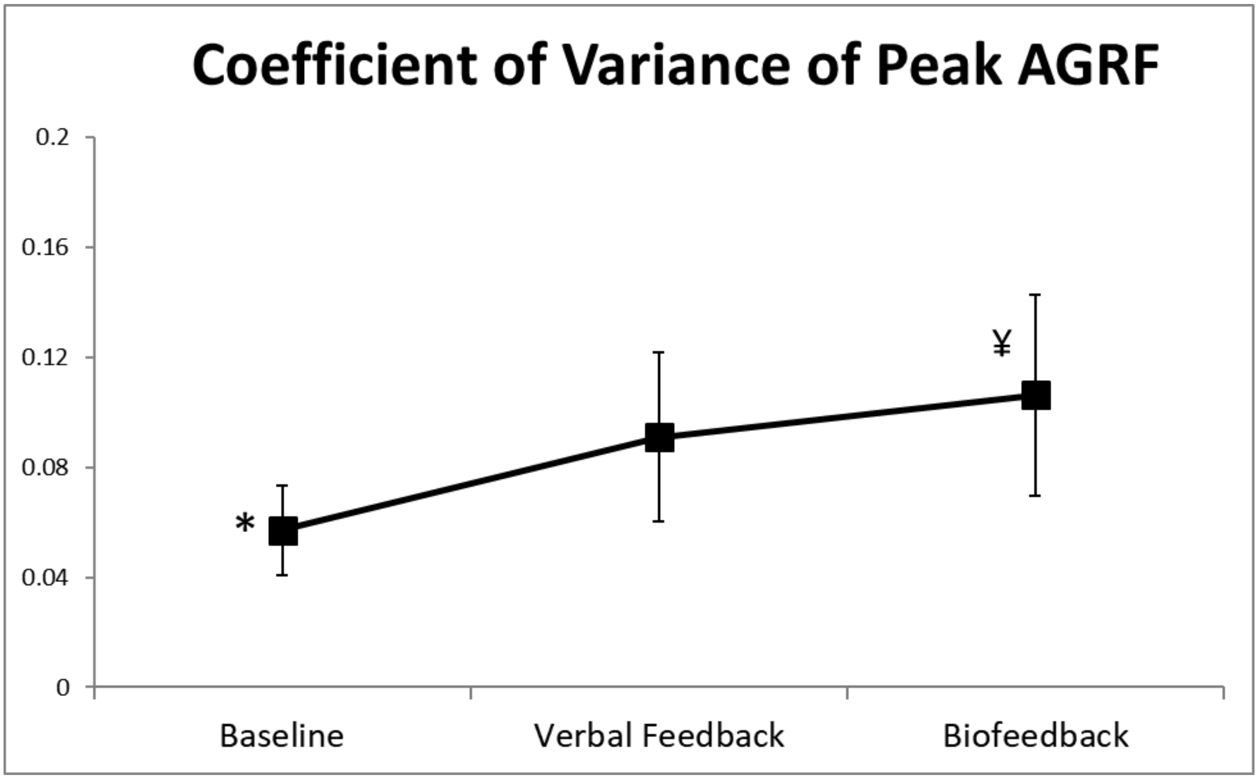

Figure 6. Right leg stride-to-stride coefficient of variance (CV) of peak AGRF for the study participants (N=7) for baseline, verbal feedback, and real-time biofeedback trials. The * symbol indicates a significant main effect of trial condition detected by the 1-way repeated measures ANOVA. The 1-way repeated measures ANOVA revealed a significant main effect of trial condition on right leg CV of AGRF. Post-hoc Bonferroni-corrected pairwise comparisons showed a statistical trend ($p<0.10$) towards a difference in CV of right leg peak AGRF between the real-time biofeedback trial and baseline (denoted by the ¥ symbol). No significant differences in right leg CV of AGRF were observed between baseline and verbal feedback, and real-time biofeedback and verbal feedback.

Table 1. Participant engagement ratings for verbal feedback and real-time biofeedback trials (1-10 scale).

Participant	Verbal Feedback	Real-time Biofeedback
1	4	8
2	3	5
3	2	7
4	6	8
5	10	9
6	6	8
7	3	4
Average	**4.9**	**7**
Stdev	**2.7**	**1.8**

biofeedback. We hypothesized that when receiving quantitative, real-time AGRF information along with a target AGRF to reach, participants would increase AGRF production in the target leg to a greater magnitude compared to when receiving qualitative, verbal feedback. However, our results suggest that through verbal instruction alone, able-bodied individuals can preferentially increase AGRF in the targeted leg to a similar degree as instrumented, real-time biofeedback.

Previous studies have demonstrated that able-bodied individuals can increase push-off forces by about 27% in response to verbal instruction [55-57]. Given that the AGRF biofeedback target set for participants was arbitrarily set to only 25% greater than baseline, participants in our study may have found success during the real-time biofeedback trial using similar biomechanical strategies to increase AGRF employed during verbal feedback training, leading to very similar increases in AGRF production across both trials. Future studies should consider increasing the biofeedback target to an even greater amount and observe whether more challenging AGRF targets during biofeedback training can induce even greater push-off forces in able-bodied individuals. It is also possible that verbal feedback is equally as effective as real-time biofeedback for increasing AGRF during shorter exposures; it may be possible that under longer walking conditions, differences in AGRF production between the verbal biofeedback trial and real-time biofeedback trial may be observed. However, our study did not investigate the effects of verbal feedback and real-time biofeedback on AGRF production for longer bout durations. Future studies should consider comparing the effects of verbal feedback and real-time biofeedback on AGRF production under longer training conditions that more closely reflect rehabilitative sessions. Moreover, additional studies may want to compare the effects of verbal feedback and real-time biofeedback on other gait biomechanical variables that contribute to improved walking function, such as trailing limb angle.

Furthermore, our results indicate that in able-bodied individuals, both verbal feedback and real-time biofeedback targeting a single leg may increase AGRF production unilaterally in the targeted leg without changes to AGRF in the non-targeted leg. Training modalities that provide preferential practice to a targeted leg without inducing changes in the non-targeted leg may serve as a useful treatment strategy for the post-stroke population. Hemiparetic post-stroke individuals commonly exhibit reduced force production in their paretic leg, and therefore require specific practice to their paretic leg while avoiding compensatory actions in their non-paretic leg. Indeed, previous studies on post-stroke individuals have demonstrated that real-time biofeedback training can unilaterally increase AGRF production in the paretic leg without concurrent increases in AGRF in the non-paretic leg [53]. However, there is a paucity of research comparing the effects of verbal feedback and real-time biofeedback on propulsive force generation in post-stroke individuals. Future studies will need to determine whether post-stroke individuals, in response to verbal feedback, increase push-off forces in the paretic limb to the same extent as using real-time biofeedback.

We observed a significant main effect of type of feedback provided on stride-to-stride variability of AGRF. Further analysis revealed a statistical trend toward a difference in CV of peak AGRF in the right leg between baseline and the real-time biofeedback trial. No differences in right leg CV of peak AGRF were observed between baseline and the verbal feedback trial, and the verbal feedback trial and real-time biofeedback trial. We hypothesized that because real-time biofeedback provides accurate knowledge of force generation during training, there would be less variability in AGRF production compared to verbal feedback training. Surprisingly, participants exhibited more variability in AGRF production when walking with real-time biofeedback compared to with verbal feedback. Because able-bodied individuals normally exhibit inter-limb symmetry during walking, the acquisition of a modified gait pattern may increase variability of force generation between strides. Moreover, the increased variability in AGRF production during the biofeedback trial may come from the lack of instruction for precision. Participants were not instructed to increase their AGRF in the targeted leg to move the “X” cursor to exactly reach the target AGRF; rather, participants were simply instructed to increase their AGRF in the targeted leg to move the “X” cursor to surpass the target. With these instructions, participants did not focus on being precise with their AGRF production in the targeted leg.

Real-time biofeedback training, as opposed to verbal feedback training, provides accurate biological and physiological information to participants that allows them to self-monitor their progress and performance. Participants in our study reported significantly higher engagement during trials when receiving real-time biofeedback compared to verbal feedback (7±1.8 out of 10 for real-time biofeedback, compared to 4.9±2.7 out of 10 for verbal feedback). Participant engagement is an important aspect of rehabilitation, given that training strategies that are engaging and motivating may enhance neuroplasticity and motor learning [58,59]. Additional investigation is needed to measure the engagement level of post-stroke patients when receiving verbal feedback versus real-time biofeedback. Our study uses a simple 1-10 self-reported scale of engagement rating; future studies should include the use of a validated engagement scale. Nonetheless, our results show that participants overwhelmingly agreed that real-time biofeedback was more engaging than verbal feedback during walking.

In summary, this study demonstrates that able-bodied individuals can increase targeted leg AGRF in response to verbal feedback and real-time biofeedback without concurrent increases in the non-targeted leg. This study illustrates the promise of biofeedback in the rehabilitative setting in that it induces improvements in AGRF unilaterally in the target leg. More importantly, our results suggest that compared to traditional verbal feedback, real-time biofeedback is more engaging and interesting, which may contribute to greater improvements during training in a rehabilitative setting. Future studies should investigate and compare the effects of verbal feedback and real-time biofeedback on walking outcomes in a post-stroke population.

3. COMPARING THE EFFECTS OF AGRF AND TLA BIOFEEDBACK ON GAIT PROPULSIVE FORCES AND GAIT BIOMECHANICS

Paretic propulsion, defined as the anterior component of the ground reaction force (AGRF), is an important post-stroke gait deficit to address due to its relationships with hemiparetic severity, walking speed, and walking function [35,40-44]. Previous studies suggest two major biomechanical parameters that contribute to propulsive force generation: ankle plantar flexor moment and trailing limb angle [46]. Several studies support the finding that ankle moment is strongly correlated to propulsive force generation and walking speed in both able-bodied and post-stroke individuals [43,60,61]. Increasing trailing limb angle (TLA), defined as the angle between the lab's vertical axis and a vector joining the greater trochanter and the fifth metatarsal head marker, may increase AGRF by allowing a greater component of the ground reaction force to be directed anteriorly.

Although both ankle moment and TLA contribute to increasing AGRF, Hsiao et al. recently demonstrated that post-stroke individuals increase AGRF in the paretic leg mainly through increases in TLA, with minimal contribution from ankle plantar flexor moment [45]. Thus, targeting deficits in TLA may be a viable strategy to increasing propulsive forces and walking function in post-stroke individuals.

Real-time biofeedback is a potent gait retraining tool that can display information to users regarding specific gait variables during training. Previous studies that utilized step-length biofeedback for post-stroke individuals demonstrated improvements in walking speed and step-length symmetry following training [50,51]. Our previous study using AGRF biofeedback in a stroke population resulted in significant increases of AGRF production in the paretic leg [53]. In addition to significantly increasing AGRF production in the paretic leg, our study also demonstrated improvements in TLA of the paretic leg, although these improvements were not statistically significant. In the stroke population, TLA may be a more appropriate variable to deliver compared to AGRF via biofeedback because it is a more specific biomechanical solution to achieving greater paretic leg propulsion. However, no study has investigated the use of TLA biofeedback and its effects on propulsive forces and gait biomechanical variables.

This study will, for the first time, investigate and compare the effects of TLA biofeedback and AGRF biofeedback on gait propulsion and biomechanics. We hypothesize that TLA feedback will induce greater improvements in TLA compared to AGRF biofeedback, and induce increases in AGRF that are similar to increases induced by AGRF biofeedback.

Methods

Seven able-bodied individuals (age = 25±3.1 years, 2 females) participated in one session of treadmill walking at a self-selected speed. Participants were excluded if they had a musculoskeletal or neurological disorder affecting gait. All participants provided informed consent and the study was approved by the Institutional Human Subjects Review Board.

Marker setup and determination of self-selected speed

Reflective markers were attached to the trunk, pelvis, and bilateral thigh, shank, and foot segments. Marker position data were recorded using a 7-camera motion capture system (Vicon Inc., Colorado, USA). Participants walked on a dual-belt treadmill equipped with force platforms (Bertec Corporation, Ohio, USA), with one foot on each belt to allow for collection of ground reaction force data from each leg. For safety, participants utilized a suspended handrail located at the front of the treadmill. Participants were instructed to keep a light fingertip touch on the handrail during all walking trials. At the beginning of the session, the self-selected speed of the participant was determined and all subsequent walking trials were performed at this self-selected speed.

Control trial and determination of AGRF and TLA biofeedback targets

Participants completed a 60-sec control trial of normal walking. Baseline AGRF and TLA values were collected during this 60-sec control trial. The AGRF targets used for AGRF biofeedback were calculated as 25% greater than baseline AGRF for the right (targeted) leg. The TLA targets used for TLA biofeedback were calculated as 25% greater than baseline TLA for the right leg.

Methodology for biofeedback

Visual and auditory biofeedback was provided using a screen placed in front of a treadmill and speaker. The visual component of AGRF biofeedback consisted of a horizontal line with a cursor (X) that represented the current AGRF for the right leg only (MotionMonitor, Illinois, USA) (Figure 7). The visual component of TLA biofeedback consisted of a horizontal line with a cursor (X) that represented the current TLA for the right leg only (Figure 8). The audio component of biofeedback consisted of an audible beep when the cursor entered the biofeedback target range during each gait cycle, signaling success. The AGRF targeted range was represented by a green line with a 5-Newton error-tolerance. The TLA targeted range was represented by a green line with a 2-degree error-tolerance.

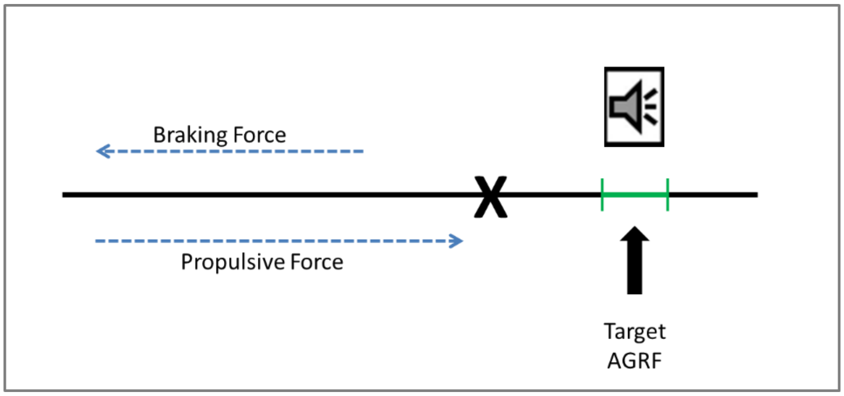

Figure 7. AGRF biofeedback interface. Participants received biofeedback on their AGRF production in their right leg during the AGRF biofeedback trial. The "X" symbol represents the current AGRF generated in the right leg during the stride cycle, and the green field goal represents the target AGRF set for the right leg. An auditory tone is produced when the "X" reaches or surpasses the green field goal, indicating successful achievement of the target AGRF during the step cycle. Adapted from Schenck and Kesar, 2017.

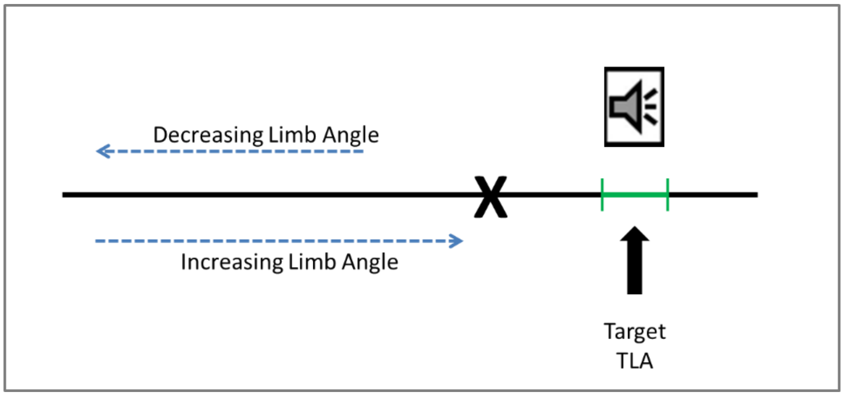

Figure 8. TLA biofeedback interface. Participants received biofeedback on their TLA in their right leg during the TLA biofeedback trial. The “X” symbol represents the current TLA in the right leg during the stride cycle, and the green field goal represents the target TLA set for the right leg. An auditory tone is produced when the “X” reaches or surpasses the green field goal, indicating successful achievement of the target TLA during the step cycle. Adapted from Schenck and Kesar, 2017.

AGRF and TLA biofeedback trials

Participants completed one 60-sec trial of walking at their self-selected speed with AGRF biofeedback provided for the right leg, and one 60-sec trial with TLA biofeedback provided for the right leg. Among all participants, the order of type of biofeedback provided (AGRF or TLA) was randomized. Participants were provided with a short standing break in between walking trials. Prior to the start of each biofeedback trial, participants received scripted, verbal instructions about the biofeedback interface, type of biofeedback that would be provided, and the training task. For the AGRF biofeedback trial, participants were instructed to push back hard enough to move the cursor to the target AGRF range. For the TLA biofeedback trial, participants were instructed to bring their right leg far back enough to move the cursor to the target range.

Dependent Variables and Data Analysis

Primary Dependent Variables

The primary dependent variables to comparing AGRF biofeedback and TLA feedback were peak AGRF and peak TLA in the right (targeted) leg. Secondary variables included peak AGRF and peak TLA in the left (non-targeted) leg. The peak AGRF was calculated as the peak value of the anteriorly directed ground reaction forces during the terminal double support phase of the leg. The peak TLA was calculated as the maximum angle between the floor's vertical axis and a line joining the greater trochanter and fifth metatarsal head marker during terminal stance.

Statistical Analyses

A 1-way repeated measures ANOVA was performed to evaluate the effect of type of biofeedback variable provided (baseline, AGRF, TLA) on each dependent variable (peak AGRF, peak TLA). Planned, paired t-tests with Bonferroni correction were conducted to compare baseline data with each type of biofeedback (AGRF, TLA) as well as to compare between AGRF and TLA biofeedback trials. Significance level was set at $\alpha \leq 0.05$ for all tests.

Results

Peak AGRF of the right (targeted) leg

The 1-way repeated measures ANOVA showed a significant main effect of biofeedback on the peak AGRF of the right leg ($p<0.001$, $F=29.150$) (Figure 9). The paired t-test showed a significant difference in peak AGRF of the right leg between baseline and the AGRF biofeedback condition ($p=0.001$) and TLA biofeedback condition ($p=0.007$). There was no significant difference in peak AGRF of the right leg between the AGRF and TLA biofeedback conditions ($p=0.219$).

Peak AGRF of the left (non-targeted) leg

The 1-way repeated measures ANOVA showed no main effect of biofeedback on the peak AGRF of the left leg ($p=0.089$, $F=2.979$) (Figure 9).

Peak TLA of the right leg

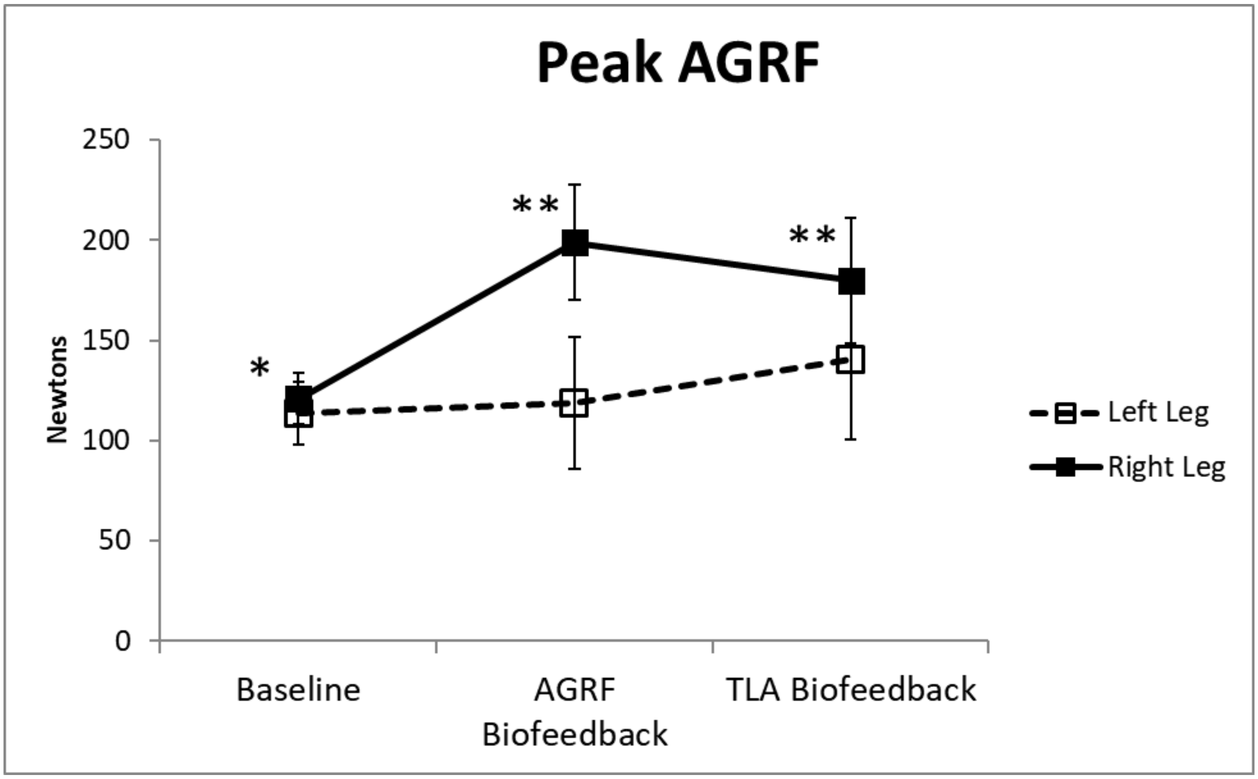

Figure 9. Average (N=7) peak AGRF for the right (targeted) and left (non-targeted) legs during baseline, AGRF biofeedback, and TLA biofeedback trials. The * symbol indicates a significant main effect detected by the 1-way repeated measures ANOVA. The 1-way repeated measures ANOVA shows a significant main effect of biofeedback on AGRF production in the right leg. The ** symbol indicates a significant difference in AGRF production in the right compared to baseline. Pairwise comparisons reveal a significant difference in right leg AGRF in the AGRF biofeedback trial and TLA biofeedback trial compared to baseline. No significant differences in right leg AGRF were observed between the AGRF biofeedback and TLA biofeedback trials.

The 1-way repeated measures ANOVA showed a significant effect of biofeedback on the peak TLA of the right leg ($p<0.001$, $F=24.867$) (Figure 10). Pairwise comparisons revealed a significant difference in peak TLA of the right leg between baseline and AGRF biofeedback ($p=0.003$) and TLA biofeedback ($p=0.005$). The pairwise comparison also revealed a significant difference in peak TLA of the right leg between the AGRF and TLA biofeedback conditions ($p=0.032$).

Peak TLA of the left leg

The 1-way repeated measures ANOVA showed a significant main effect of biofeedback on peak TLA of the left leg ($p=0.004$, $F=9.008$) (Figure 10). Pairwise comparisons revealed a significant difference in peak TLA of the left leg between baseline and TLA biofeedback ($p=0.042$) and between AGRF biofeedback and TLA biofeedback ($p=0.005$). No significant difference in peak TLA of the left leg was observed between baseline and AGRF biofeedback ($p=1.000$).

Discussion

This study compared the effects of AGRF biofeedback and TLA biofeedback on gait propulsive forces and biomechanics. During a 60-sec trial of AGRF biofeedback, study participants significantly increased their right (targeted) leg AGRF production compared to baseline. No significant increases in left (non-targeted) leg AGRF production were observed during the AGRF biofeedback and TLA biofeedback trials. These results align with the findings of our previous studies investigating the use of AGRF biofeedback in able-bodied and post-

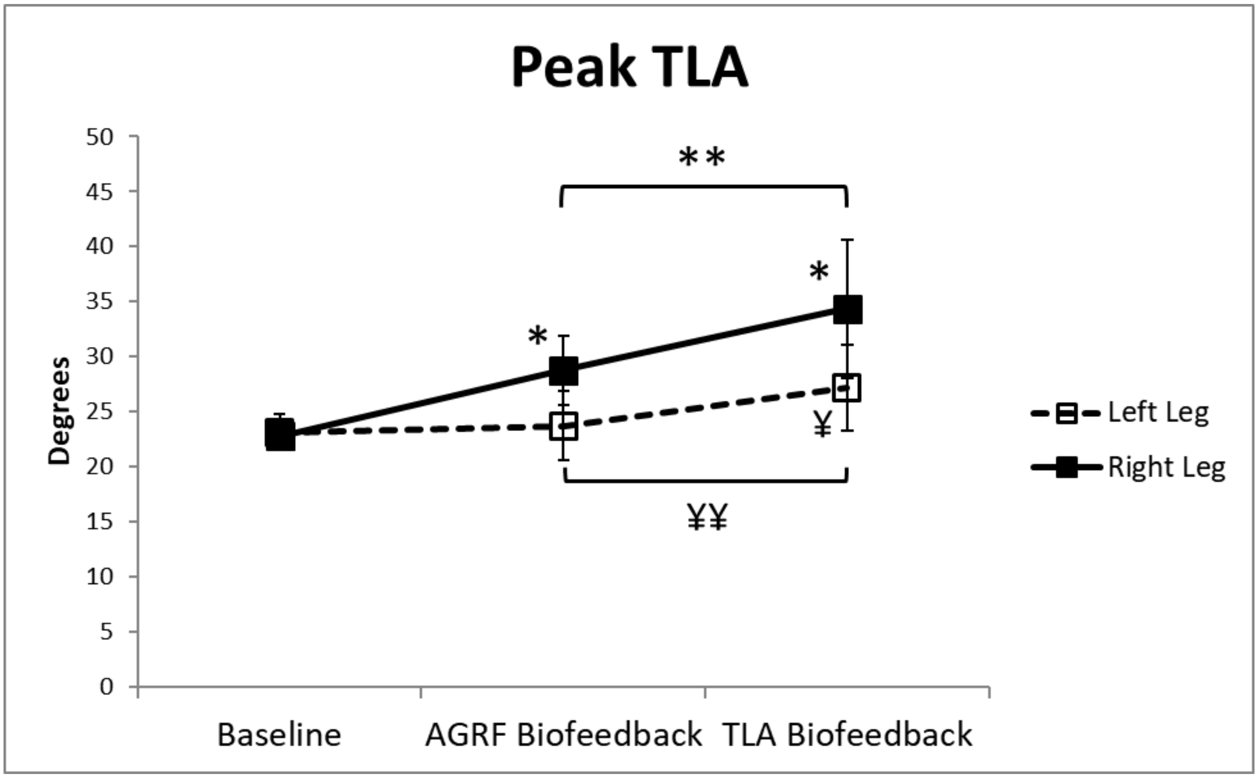

Figure 10. Average (N=7) peak TLA for the right (targeted) and left (non-targeted) legs during baseline, AGRF biofeedback, and TLA biofeedback trials. The 1-way repeated measures ANOVA showed a significant main effect of right leg peak TLA. The * symbol indicates a significant difference in right leg peak TLA compared to baseline. Paired t-tests reveal a significant increase in right leg peak TLA in the AGRF biofeedback trial and TLA biofeedback trial compared to baseline. Pairwise comparisons also show a significant increase in right leg peak TLA during the TLA biofeedback trial compared to the AGRF biofeedback trial (denoted by the ** symbol). The ¥ symbol indicates a significant difference in left leg peak TLA compared to baseline. Pairwise comparisons show a significant difference in left leg peak TLA in the TLA biofeedback trial compared to baseline. Pairwise comparisons also reveal a significant difference in left leg peak TLA between the TLA biofeedback and AGRF biofeedback trials (denoted by ¥¥). No differences in left leg peak TLA were observed between the AGRF biofeedback trial and baseline.

stroke populations [53,54]. More specifically, we show in our previous studies and here that the use of AGRF biofeedback induces improvements in push-off forces in the targeted leg with no concomitant increases in push-off forces in the non-targeted leg.

Our results also show that during walking with AGRF biofeedback, participants significantly increased right leg peak TLA compared to baseline. There were no significant differences in left leg peak TLA during AGRF biofeedback training compared to baseline. When receiving instructions for the AGRF biofeedback trial, participants were not informed of biomechanical strategies that could be used to increase AGRF; rather, we let individuals explore and develop their own biomechanical solutions to achieving adequate propulsion. The finding that study participants increased AGRF in the target leg concurrently with increases in TLA indicate that participants utilized appropriate biomechanical strategies to increase propulsion. Biomechanically, TLA is one of the most important strategies to increasing AGRF, and our results strengthen previous reports showing TLA as an important predictor of AGRF production [43,45-47].

To our knowledge, this is the first study that systematically evaluates the effects of exposure to TLA biofeedback on gait variables in able-bodied individuals. During a 60-sec trial with TLA biofeedback, participants showed significant increases in TLA compared to baseline. Moreover, TLA biofeedback induced a significantly greater peak TLA compared to AGRF biofeedback. This finding demonstrates the feasibility and efficacy of TLA biofeedback in inducing improvements in TLA in an able-bodied population.

Interestingly, compared to baseline and the AGRF biofeedback trial, there were significant increases in the left (non-targeted) leg peak TLA during the TLA biofeedback trial. These results suggest that in able-bodied individuals, targeting kinetic gait variables during biofeedback, such as TLA, may induce bilateral changes to gait biomechanical variables. On the other hand, targeting kinetic variables during biofeedback, such as AGRF, results in more unilateral changes to gait. Able-bodied individuals may be less tolerant to changes in kinematic variables compared to kinetic variables in the targeted leg, and therefore may respond with changes to the non-targeted leg.

These results have important implications for the proposed unilateral effects of gait biofeedback training. Post-stroke patients benefit from training strategies that target the paretic leg while avoiding the strengthening of compensatory mechanisms in the non-paretic leg to improve walking function. Our previous studies and current study show that exposure to AGRF biofeedback induces changes to AGRF and TLA in only the targeted leg. However, our current study demonstrates that TLA biofeedback induces significant changes in TLA in both legs rather than solely the targeted leg. Post-stroke patients may, however, benefit from increases in TLA in both legs given that post-stroke individuals exhibit shortened stride length in both legs and increases in TLA may improve stride length. Although TLA biofeedback may induce changes to both legs, it is important to note TLA biofeedback did preferentially increase the TLA of the targeted leg, indicated by greater magnitude of change in TLA observed in the right (targeted) leg compared to left (non-targeted) leg.

Following a 60-sec trial with TLA biofeedback, participants significantly increased their right leg AGRF production compared to baseline. More notably, there were no significant differences in right leg AGRF production between the AGRF biofeedback trial and TLA biofeedback trial. These findings suggest that comparable improvements in propulsive force generation may be achieved through the delivery of biofeedback variables other than AGRF. This is an important consideration for the search for appropriate biomechanical variables to deliver via biofeedback to the post-stroke population. Our previous study using AGRF biofeedback did not provide instructions regarding specific biomechanical strategies post-stroke participants could use to increase push-off forces. Instead, participants were encouraged to explore different movement and gait patterns to increase paretic AGRF. By delivering a more specified biomechanical variable closely linked to AGRF via biofeedback, post-stroke individuals may be better able to improve push-off forces in addition to other gait variables associated with improved walking outcome. For example, our previous study showed that following AGRF biofeedback training, post-stroke individuals demonstrated slight increases in peak TLA in the paretic leg; however, these improvements were not statistically significant [53]. In our current study, the use of TLA biofeedback in able-bodied individuals resulted in significant increases in both AGRF and TLA in the targeted leg. In a post-stroke population, the effects of TLA biofeedback on propulsive forces and biomechanical variables remain unknown. Therefore, the use of TLA biofeedback in a post-stroke population merits additional investigation.

One potential limitation of our study is that participants utilized a handrail during all walking trials. The use of a handrail may result in a forward trunk lean that disrupts accurate measurement of trailing limb angle. However, participants were continuously reminded to keep a light fingertip touch on the hand rail throughout the session to minimize the use of handrail support.

In conclusion, this study investigated and compared the effects of AGRF biofeedback and TLA biofeedback on gait propulsive and biomechanical forces. Given the feasibility and efficacy of TLA feedback on inducing improvements in TLA and AGRF, there is a need for the investigation of this training strategy in individuals post-stroke.

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5. APPENDIX

Verbal feedback trial script:

"We will begin the treadmill at your comfortable walking speed while holding onto the treadmill. This time I will be giving you verbal instructions throughout the trial. With your right leg only, I want you to push back into the ground. To help understand what I mean, I would like to show you this picture. As you see in the image, focus on the leg about to step off, notice the arrow pushing the ground backward. That is the direction of push-off I want you to focus on during the next walk. I will also intermittently instruct you to push back into the ground harder. You will be walking at your comfortable walking speed while holding onto the handrail."

Picture depicting AGRF shown to participants prior to verbal feedback trial: