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Zahin Alam April 12, 2022

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A Preliminary Investigation

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
of Emory University in partial fulfillment
of the requirements of the degree of
Bachelor of Sciences with Honors

Department of Biology

2022

Abstract

Introduction: Hemiparesis is characterized by decreased motor control and consequential muscle weakness on one side of the body, often termed the “paretic” side. Hemiparesis leads to biomechanical deficits in the paretic leg and inter-limb asymmetry, reducing walking function and mobility. One concomitant effect of hemiparesis is the reduction of propulsion in the paretic leg of stroke survivors. Gait interventions have targeted the paretic leg to increase paretic propulsion to be closer in magnitude relative to the non-paretic leg propulsion, reducing inter-limb propulsive asymmetry between the paretic and non-paretic limbs. Along with reduced propulsion, hemiparesis may alter the timing of propulsion. This thesis explores the utilization of real-time video game-based biofeedback as a gait rehabilitative strategy targeting paretic propulsion. Video games have been shown to create a more engaging and motivating training session and may help to distract users from fatigue or boredom. Our premise is that by taking advantage of game-based elements, video game biofeedback may make gait rehabilitation more fun and more engaging, thus maximizing therapeutic efficiency of restoring proper propulsion.

Methods: During a gait analysis session, three able-bodied participants (1 female, age 21.3 ± .58 y) and one post-stroke participant (69 y) were exposed to 3 walking conditions - no biofeedback, conventional biofeedback (Motion Monitor), and video game biofeedback (RockWalk). In addition to propulsion, measured using anteriorly directed ground reaction forces (AGRFs), we also recorded heart rate (using a chest-mounted monitor) and skin impedance (using a portable sensing device attached to the fingertips). Additionally, after each trial, participants were asked to report their rating of perceived exertion and score on an engagement questionnaire.

Outcome/measurements: The primary outcome measures were peak AGRF magnitude, coefficient of variance (CoV) of peak AGRF magnitude, timing latency of peak AGRF during the gait cycle, and CoV of peak AGRF timing. Secondary outcomes included average heart rate, skin conductance response (SCR), rating of perceived exertion (RPE), and engagement questionnaire scores.

Results: Compared to no biofeedback, video game biofeedback (RockWalk) induced a significantly greater peak AGRF magnitude and an increase in stride-to-stride variability of peak AGRF magnitude. There was no significant change in timing of peak AGRF, but RockWalk induced a small decrease in the latency of peak AGRF relative to ipsilateral toe-off. Moreover, there was a decrease in the stride-to-stride variability of peak AGRF timing. For able-bodied participants, RockWalk induced the highest skin conductance response, average heart rate, and average RPE. The engagement questionnaire showed that RockWalk was found to be more creative and faster-paced than Motion Monitor, though both Motion Monitor and RockWalk were found to be similarly enjoyable and engaging. Our case-study on one stroke survivor also demonstrated the feasibility and immediate effects of the video game biofeedback for improving propulsion in people with post-stroke hemiparesis.

Discussion: Our preliminary results show that video game biofeedback can increase the magnitude of propulsion of the targeted leg without changing propulsion magnitude in the non-targeted leg of healthy individuals. Timing analysis suggests that timing of peak AGRF may be tightly controlled despite changes in walking conditions (e.g. different speeds, with biofeedback) in healthy individuals, though biofeedback may induce greater stride-to-stride consistency in timing of peak AGRF. Lastly, video game biofeedback induced greater exercise intensity (average heart rate), perceived effort (RPE), and was reported to be more creative and fast-paced, though engagement was subjectively similar to a basic biofeedback interface. Taken together, these results support the feasibility of utilizing our novel video game biofeedback interface as a gait rehabilitative tool, and pave the way for future studies exploring the effects of video game biofeedback in individuals post-stroke with propulsive gait deficits.

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Acknowledgements

I would like to acknowledge Dr. Kesar for accepting me into her lab three years ago, and giving me the opportunity to grow as a researcher and scientist. Without her support, I would not have been as enthusiastic about science as I am now.

I would like to acknowledge Joseph, who was phenomenal in his support with helping me with my projects and aiding in data collection and data analysis for my thesis. He is an amazing mentor.

I would like to acknowledge Dr. Rendos for helping me with our timing projects and Visual 3D pipelines, making my life with data analysis so much easier.

I would like to acknowledge the other fellow undergraduate researchers in my lab, Min and Vrushali, for helping with data collection and allowing me to learn and grow as their mentor.

I would like to acknowledge my Computer Science whiz friend Noah Okada for helping me learn MATLAB to help process SCR data.

I would like to acknowledge my friends (and due to privacy I cannot mention their names, but you know who you all are!) for volunteering to be my subjects for this thesis.

And finally, thank you to my parents for always supporting me in what I do.

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1. THE EFFECT OF DIFFERENT MODES OF BIOFEEDBACK INTERFACES ON THE GENERATION OF PROPULSION

Introduction

Stroke is the leading cause of long-term disability in the United States [6]. Stroke damages neural circuitry in the central nervous system [45] and can lead to a particular condition called hemiparesis [47]. Hemiparesis is characterized by decreased motor control and consequential muscle weakness on one side of the body, often termed the “paretic” side. Hemiparesis leads to biomechanical deficits in the paretic leg and inter-limb asymmetry, reducing walking function and mobility [4,13]. One concomitant effect of hemiparesis is the reduction of propulsion in the paretic leg of stroke survivors [4,8,44]. This symptom has been identified as a potential therapeutic target as the generation of propulsion is an important component of gait, enabling smooth stance to swing transition and imparting acceleration to the center of mass [44]. Reduced propulsion has been associated with gait asymmetry, inefficient energy expenditure, and slowed walking speeds [4,8,44]. The magnitude of propulsion is measured using a force platform embedded in the floor or treadmill, which collects anteriorly directed ground reaction forces (AGRF). Thus, many rehabilitative strategies have been clinically studied to address this gait deficit and increase the magnitude of propulsion generated. Such strategies include high-intensity treadmill training [43], functional electrical stimulation [2], and gait biofeedback [20,37,38,49].

Several of these gait interventions have targeted the paretic leg to increase paretic propulsion. Increasing magnitude of paretic propulsion to be closer relative to the magnitude of generated non-paretic propulsion can reduce inter-limb asymmetry between the paretic and non-paretic limb. Increase in magnitude of paretic propulsion has been accompanied by increase in walking speeds and efficient energy expenditure of post-stroke individuals [3,9,23]. Thus, there have been multiple studies that have provided evidence that preferentially targeting paretic propulsion provides gait benefits for stroke survivors. Furthermore, therapeutically targeting the paretic leg in comparison to providing stepping practice to both legs likely aid in discouraging overcompensation from the non-paretic leg. Given the importance of paretic propulsion as a post-stroke gait deficit, further research is needed to explore novel and efficacious gait training interventions.

Real-time biofeedback training has been identified as a promising intervention for targeting specific biomechanical impairments [21,50,51]. Biofeedback training induces behavior changes by providing the user with real-time information on a specific targeted variable [21,50,51]. Through biofeedback, the user can integrate the information provided to them for self-correction of aberrant gait patterns and enhance their individual self-awareness of the targeted impairment [21,50,51]. Previous studies within the lab have shown that gait biofeedback can be used to increase target AGRF in able-bodied and post-stroke individuals [20,49]. From there, research has then transitioned into analyzing the efficacy of different modes of biofeedback in increasing paretic propulsion. For example, Liu et. al has shown that basic audio, visual, and audiovisual biofeedback increased paretic propulsion in post-stroke individuals [37]. Thus, there has been a development of research looking into utilizing biofeedback interfaces for gait rehabilitative purposes.

There are several challenges to gait rehabilitation that interface-based biofeedback can help tackle. First, there is a paucity of customizable gait interventions that individually target a stroke survivor’s specific gait deficits, culminating in a lack of alternatives to the “one-size-fits-all” approach. Second, there is a need to induce higher patient engagement, motivation, and salience in order to enhance motor learning and neural plasticity [29,30]. Third, limited therapy time with the patient has required a need to maximize therapeutic efficiency of out-patient rehabilitation, and moreover improve home-based exercise prescription. By translating rehabilitative methods to outside a clinical setting, there is potential for providing the thousands of steps needed to implement long-term gait changes [10,27] that would not be induced by the relative low number of steps produced in clinical interventions [33]. As a result, there is an importance in the selection of an interface-based biofeedback that can develop personalized, engaging, and salient gait training that additionally addresses several of these challenges faced in the rehabilitative field.

This study will look to incorporate and implement gaming interfaces for gait biofeedback. “Gamification” is a term that describes using game-elements in non-gaming environments to improve user engagement and shape behavior [4,19]. Games provide a more engaging experience by encouraging higher effort, offering replayability, and rewarding desirable performance, which are strong goals of rehabilitation [36].Thus, rehabilitative interventions should look to take advantage of these qualities to increase patient engagement, motivation, exercise intensity, and help shape healthy behavior. By designing a more interesting and enjoyable game interface compared to traditional therapy tasks, rehabilitation sessions can become more fun for patients. Further advantages of games include the use of cues to provide accurate and immediate information about movement performance, the discouragement of maladaptive behavior and compensations, and the ability to personalize to each client by modifying task-difficulty [19,36,40,53]. When video games were used for upper-limb rehabilitation, users relayed that the game made rehabilitation more entertaining and helped achieve greater exercise intensity [34].

Specialized game-based tools that target gait deficits are currently not commercially available in rehabilitation clinics. However, game software and programming available to game-designers and computer scientists provide an immense opportunity to explore potential uses of video game technology in a clinical setting. The first chapter of this thesis will explore the preliminary results of the effect of video game biofeedback interface on targeting and modulating paretic propulsion. We hypothesize that the video game biofeedback, titled "RockWalk," will induce the highest increase in paretic AGRF compared to the basic gait biofeedback interface (Motion Monitor, Illinois, USA) and no biofeedback exposure.

Methods

Three able-bodied participants (1 female, age 21.3 ± .58 y) and one post-stroke participant (69 y) completed a single-gait analysis session in the Motion Analysis Laboratory. All participants provided consent approved by the Institutional Review Board. Inclusion criteria included more than six months post-stroke, ability to complete one-minute continuous walking, and can communicate with the investigators. Exclusion criteria included neurologic diagnosis outside of stroke, hemineglect, cerebellar dysfunction, and orthopedic conditions that constrained walking function. Each participant was strapped with a heart rate monitor around their chest and a bio-signaling device around the pointer and middle finger of their left hand to measure physiological responses (heart rate and electrodermal activity; see Chapter 3) to biofeedback exposure.

Selection of Self-Selected Speed

Each participant initially walked on the split-belt treadmill to familiarize themselves with the lab environment. Afterwards, participants were instructed to walk on the treadmill, with the treadmill speed increased by 0.1 m/s increments until the participant reported their self-selected comfortable walking speed. Ground reaction force data were captured using force platforms embedded within a split-belt treadmill at 1000 Hz (Bertec Inc., Columbus, Ohio, USA). All successive trials were performed at self-selected speed. Participants were provided support using an overhead safety harness as well as had a handrail to hold. Each participant was instructed to maintain a consistent grip on the handrail throughout each trial. Furthermore, if there were any visual cues that the participant possessed an excessive reliance on the handrail or excessive trunk lean to support their gait, then that particular gait trial was redone.

Control Trial and Calculating Target AGRF

Each participant completed a thirty second trial of normal walking, where their baseline AGRF was collected by the force platforms in the split-belt treadmill. The target AGRFs used for the modes of biofeedback for abled-bodied individuals were calculated to be 15% greater than their baseline AGRF of their dominant leg. Afterwards, able-bodied participants completed a sixty second control trial of baseline walking with no instruction.

On the contrary, the post-stroke individual first walked sixty seconds of baseline walking with no instruction. Based on the baseline AGRF from the control trial, five target AGRF values were generated (Equation 1) using paretic and non-paretic peak AGRFs measured during the baseline trial to set a challenging, individualized target AGRF for each participant. Inter-limb deficits are much greater in post-stroke individuals than able-bodied participants, and as a result, a target paretic AGRF that is not too challenging nor too easy relative to their non-paretic AGRF had to be selected.

$$\text{Target AGRF} = \text{Paretic AGRF} + n(\text{nonparetic AGRF} - \text{Paretic AGRF});$$

$$n = 0.2, 0.4, 0.6, 0.8, 1.0$$

After calculation of the five target AGRF values, the participant completed five brief thirty second trials at each target value. Thirty second trials were used to minimize fatigue. The participant received instruction on the target AGRF parameter and the first biofeedback interface that they were exposed to (Motion Monitor). Target AGRF selected for the subsequent biofeedback trials corresponded to the thirty second trial where the participant achieved the target greater than 50% of gait cycles. This target AGRF calculation method was used in a previous study in the lab [11].

Methodology of Basic Audiovisual Biofeedback (Motion Monitor)

Participants completed a sixty second trial where they were each exposed to the basic audiovisual biofeedback interface (Motion Monitor). Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 1). Visual biofeedback was presented with a horizontal line with a cursor (X) that represented the real-time generated paretic AGRF. The target AGRF was represented by a green line with a 6-Newton error tolerance range centered at the AGRF target. Audio biofeedback was relayed by an audio tone that played when AGRF produced reached the target range during each gait cycle, indicating success. The participant was instructed prior to the trial that the cursor represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to reach the target range. Instructions concerning strategies to increase AGRF were not given.

Methodology of Video Game Biofeedback (RockWalk)

Participants completed a sixty second trial where they were each exposed to video game biofeedback (RockWalk). RockWalk is a visual effects game designed for gait biofeedback and takes advantage of a high-definition graphical display in contrast to the simple, non-intuitive display seen in Motion Monitor. Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 2). Visual biofeedback was presented through visual animations within a gamified environment. An avatar was placed into the game, represented by a badger with a construction hat, to enhance the immersive experience of the game design and setting. The axe works in synchronously with the generation of paretic AGRF and moves accordingly to the force produced. When generated AGRF reaches target AGRF, the axe is visually animated to strike the crystal rock which is subsequently collected by a cart, rewarding the participant with an increased game score. Audio biofeedback is comprised of a clinking sound that plays when the crystal is stricken by the axe in addition to voice-acted reinforcing statements (“that was awesome,” “good job”) vocalized by the badger character in the game. After sixty seconds, the game ends and a table presenting the final game score is shown to the player. The participant was instructed prior to the trial that the axe represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to break the crystal rocks, indicating that target AGRF was reached. Instructions concerning strategies to increase AGRF were not given.

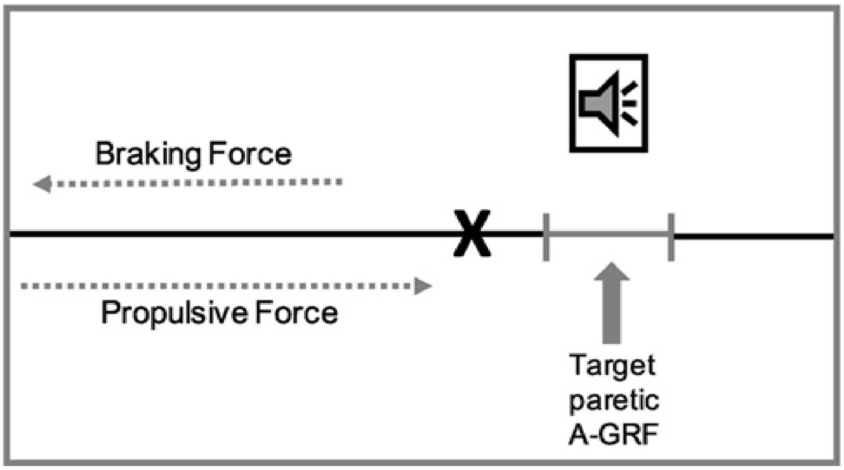


Figure 1. Schematic representing current non-game based audiovisual biofeedback. *Participants walked on a treadmill with exposure to audiovisual biofeedback. The cursor (X) indicates real-time generated AGRF during each stride cycle. The range represents the target paretic AGRF. Visual biofeedback is provided by the cursor's proximity to the target paretic AGRF range. Audio biofeedback is provided by an audible beep that indicates successful AGRF targeting.*

Figure 2. Schematic representing video game biofeedback. *Participants walked on the treadmill with exposure to the video game biofeedback interface. A) Participants are exposed to a visually animated game environment, design, and setting in addition to a game avatar. B) When generated AGRF matches target AGRF, the axe is animated to strike the crystal rock, which is subsequently collected by a cart, rewarding the player with an increase in their game score.*

Engagement and Physiological Components

After completion of sixty second trials, the average heart rate collected by the heart rate monitor of each participant was recorded. Second, each participant's electrodermal activity (EDA) over the sixty second trial was collected. Third, each participant was asked for their rating of perceived exertion (RPE) of each trial, with six representing the lowest intensity and effort and twenty representing the highest intensity and effort (Appendix). Fourth, an engagement questionnaire was given to each participant. The questionnaire provided two polarizing adjectives with 1 representing the "negative" adjective and 7 representing the "positive" adjective. Whichever number that the participant marked represented the subjective experience and attitude of each biofeedback interface (Figure 10). The results of these collected data are presented in Chapter 3 of the thesis.

Dependent Variables and Data analysis

The primary dependent variable that was measured was peak AGRF produced of the dominant leg of able-bodied participants and the paretic and non-paretic limb of post-stroke individuals. Collected GRF data from the split-belt treadmill were exported to Visual 3D. In Visual 3D, peak AGRF was calculated as the peak value of AGRF produced in terminal double support phase. Average peak AGRF of able-bodied and post-stroke participants for each condition (no biofeedback, Motion Monitor, RockWalk) were calculated and analyzed.

Statistical Analysis

A one-way repeated measures ANOVA was conducted to evaluate the effect of the different modes of biofeedback (no biofeedback, Motion Monitor, RockWalk) on the dependent variable, which is peak AGRF. If ANOVA showed a main effect, Bonferroni-corrected planned post-hoc paired comparisons were conducted to evaluate differences between no biofeedback and modes of biofeedback (Motion Monitor, RockWalk) as well as to evaluate differences between the modes of biofeedback. Significance level was set at $\alpha \leq 0.05$ for all tests. Measures of effect size in ANOVA were used to measure the degree of association between different modes of biofeedback on stride-to-stride variability of peak AGRF magnitude.

Results

Peak AGRF of the right (targeted) leg

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed significant main effect of biofeedback mode on peak AGRF of the targeted leg (p= .009, F=18.76) (Figure 3). Bonferroni-corrected post hoc paired comparisons showed significantly greater targeted peak AGRF for video game biofeedback (RockWalk) compared to no biofeedback (p=.01). There was no significant difference found between basic interface biofeedback (Motion Monitor) and no biofeedback (p=.12) and there was no significant difference found between the two modes of biofeedback (Motion Monitor, RockWalk) (p=.08).

Peak AGRF of the left (non-targeted) leg

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on peak AGRF of the non-targeted leg (p= .555, F=.683) (Figure 3).

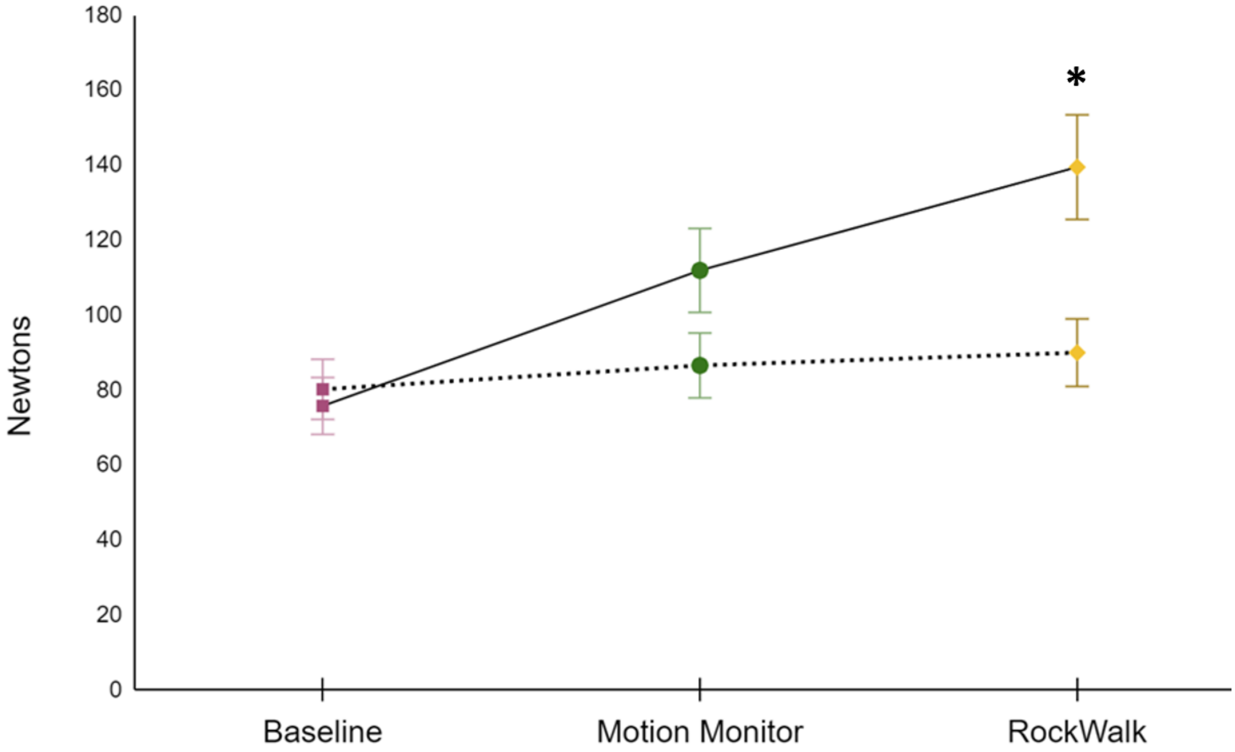


Figure 3. Peak AGRF for the targeted leg (solid line) and the non-targeted leg (dashed line) for different modes of biofeedback in able-bodied individuals. *The * indicates significant difference from the no biofeedback, or baseline, condition. Bonferroni-corrected post hoc paired comparisons showed significantly greater targeted peak AGRF for video game biofeedback (RockWalk) compared to no biofeedback. There was no significant difference found between basic interface biofeedback and no biofeedback and there was no significant difference found between the two modes of biofeedback (Motion Monitor, RockWalk). The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on peak AGRF of the non-targeted leg.*

Coefficient of variance of peak AGRF magnitude

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on the stride-to-stride variability of peak AGRF magnitude of the targeted leg (p= .173, F=2.79) (Figure 4). However, there is a small increase in stride-to-stride variability of peak AGRF magnitude. The effect size of mode of biofeedback on stride-to-stride variability of peak AGRF magnitude was $\eta^2 = .58$, indicating a strong effect of mode of biofeedback on stride-to-stride variability of peak AGRF magnitude.

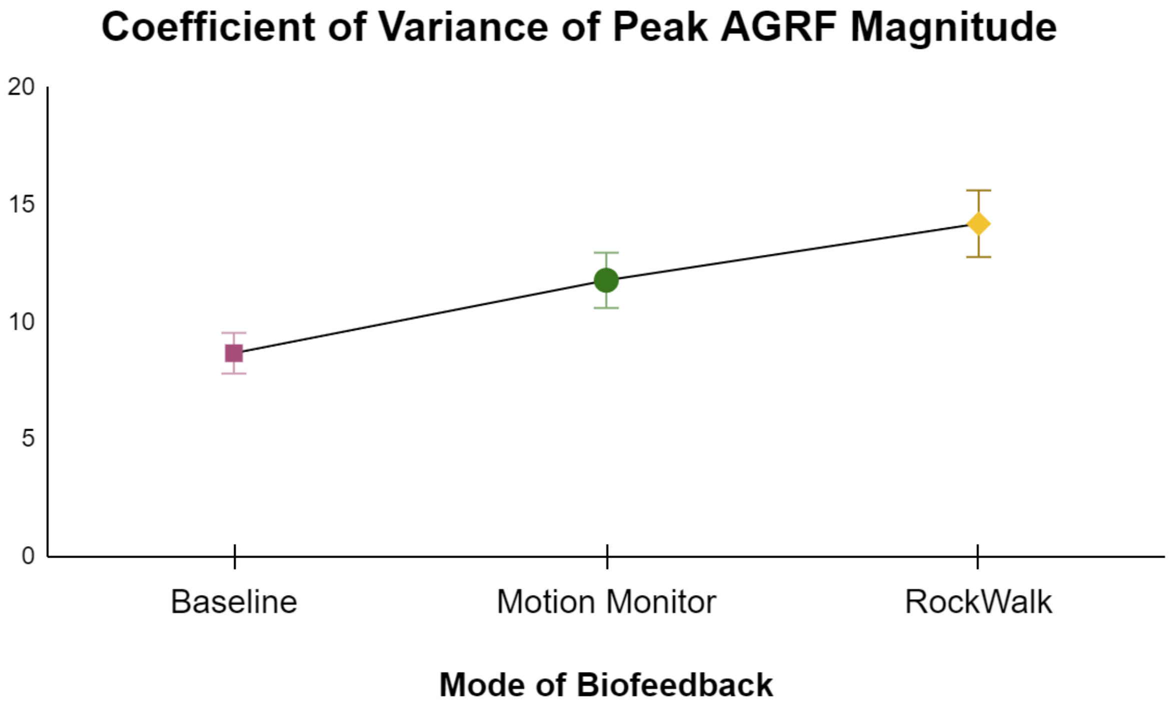


Figure 4. Mean ± SE of stride-to-stride coefficient of variance of peak AGRF magnitude of the targeted leg during baseline, conventional biofeedback interface (Motion Monitor), and video game biofeedback interface (RockWalk) walking trials of able-bodied individuals.

Discussion

This study investigated and compared the effects of video game biofeedback (RockWalk) to conventional audiovisual biofeedback (Motion Monitor) and no biofeedback (baseline). Throughout the brief sixty second trial with exposure to RockWalk, able-bodied participants significantly increased the generation of their propulsion of their targeted leg compared to no biofeedback exposure. Meanwhile, there was no significant difference in the magnitude of propulsion of the non-targeted leg when exposed to RockWalk compared to no biofeedback exposure. Similarly, Motion Monitor induced an increase in the magnitude of the targeted leg, though the increase was not significantly different compared to no biofeedback exposure. This increase was accompanied by minimal concomitant increase of propulsion magnitude in the non-targeted leg.

RockWalk exposure produced the highest magnitude of propulsion out of the three conditions. These preliminary results match our hypothesis, where we predicted that RockWalk would induce the highest magnitude of peak AGRF. While Motion Monitor also preferentially increased AGRF in the targeted leg, RockWalk exposure was the only trial to be significantly different from baseline trials in able-bodied participants. Thus, these preliminary results positively contribute to the rationale and feasibility of utilizing video game biofeedback as a potential gait rehabilitative tool. Furthermore, both Motion Monitor and RockWalk can particularly target a single leg and induce unilateral increases in propulsion forces without concomitantly increasing AGRF of the non-targeted leg. Hemiparetic post-stroke individuals possess weaker force production in their paretic limb and consequent compensatory actions in the non-paretic limb, contributing to an asymmetrical gait. Thus, several training and rehabilitative strategies aim to preferentially affect the targeted leg while maintaining the parameters of the non-targeted leg. Through this approach, gait symmetry and deficits can be improved by increasing generated paretic propulsive forces to be closer to generated non-paretic propulsive forces. However, while we have collected preliminary data on the effect of video game on AGRF production, there are several other propulsion-related biomechanical variables that play a role in maintaining healthy and effective gait. Thus, future studies should investigate the effect of video game biofeedback on other important propulsion-related biomechanical variables such as peak power and peak moment.

Along with increased magnitude of generated propulsion, we see increased stride-to-stride variability in peak AGRF after exposure to biofeedback, with RockWalk inducing the highest variability. We hypothesized that participants exposed to RockWalk would exhibit the least amount of variability due to the delivery of real-time accurate information of generated gait propulsive forces. Thus, to our surprise, preliminary results revealed the opposite effect. Quite possibly, there was an adjustment period during the trial to which the participants would learn how to break the crystal rocks and score points properly and effectively. While prior instructions and video of the game explaining the rules and objectives were given to minimize the adjustment period, there would still be a slight adjustment due to physical adaptations to the game. For example, able-bodied individuals exhibit inter-limb symmetrical gait, and thus would have to develop a modified gait pattern to successfully score points. Moreover, due to the short length of the trials (sixty seconds), this adjustment period would affect the overall variability of the trial.

Additionally, in the Motion Monitor trials, participants were asked to surpass the target range with their cursor instead of specifically targeting the range. Thus, participants may not have been focused on the precision of their generated propulsion, and instead were focusing on passing the range, contributing to the increased variability seen in Motion Monitor. Thus, future studies should explore longer bouts to minimize the effect of the adjustment period and see if variability decreases with longer sessions.

All in all, preliminary results demonstrates that video game biofeedback and conventional biofeedback can increase targeted AGRF while maintaining non-targeted AGRF in able-bodied individuals, with video game biofeedback inducing the most significant change. This study illustrates the feasibility and rehabilitative promise of video game biofeedback in unilaterally improving the targeted leg. Thus, these results warrant further studies that increase sample size, explore the effects of longer training sessions, and most importantly, translate video game biofeedback to study the walking outcomes of a post-stroke population.

2. ANALYSIS OF TIMING OF PROPULSION RELATED BIOMECHANICAL VARIABLES

2.1. Timing of Propulsion-Related Biomechanical Variables is Impaired in Individuals with Post-Stroke Hemiparesis

Abstract

Background: In individuals with post-stroke hemiparesis, reduced paretic leg propulsion, measured through anterior ground reaction forces (AGRF), is a common and functionally-relevant gait impairment. Deficits in other biomechanical variables such as plantarflexor moment, ankle power, and ankle excursion contribute to reduced propulsion. While reduction in the magnitude of propulsion post-stroke is well studied, here, our objective was to compare the timing of propulsion-related biomechanical variables.

Research Question: Are there differences in the timing of propulsion and propulsion-related biomechanical variables between able-bodied individuals, the paretic leg, and non-paretic leg of post-stroke individuals?

Methods: Nine able-bodied and 13 post-stroke individuals completed a gait analysis session comprising treadmill walking trials at each participant's self-selected speed. Planned independent sample t-tests were conducted to detect differences in the timing of dependent variables between the paretic versus non-paretic leg post-stroke and paretic leg versus the dominant leg of able-bodied individuals.

Results: Post-stroke individuals demonstrated significantly earlier timing of peak AGRF of their paretic leg versus their non-paretic leg and able-bodied individuals. Post-stroke participants displayed earlier timing of peak power of their paretic leg versus their non-paretic leg and able-bodied individuals, and earlier timing of peak ankle moment of the paretic leg versus able-bodied. No significant differences were detected in the timing of peak ankle angle.

Significance: The earlier onset of peak AGRF, peak ankle power, and peak ankle moment may be an important, under-studied biomechanical factor underlying stroke gait impairments, and a potential therapeutic target for stroke gait retraining. Future investigations can explore the use of gait biofeedback to normalize the timing of these peaks, thereby improving propulsion and walking function post-stroke.

Introduction

Post-stroke hemiparesis leads to biomechanical gait deficits in the paretic leg and inter-limb gait asymmetries, which in turn reduce walking function and mobility [44]. Generation of propulsion is a crucial component of the gait cycle, which facilitates a smooth stance to swing transition [44]. The magnitude of propulsive force, measured using a force platform as anteriorly directed ground reaction forces (AGRF), is reduced in the paretic leg of hemiparetic individuals, and associated with gait impairments and slowed walking speed [8,44]. Interventions such as high-intensity treadmill training [43], functional electrical stimulation [2], and gait biofeedback [20] have targeted paretic AGRF to improve post-stroke walking function.

Ankle moment, power, and ankle angle influence propulsion and demonstrate abnormalities in their magnitude post-stroke [25]. Plantarflexor muscles generate mechanical power enabling forward propulsion and swing initiation during late stance [17]. Reduced ankle power, moment, and ankle angle have been associated with shorter step length, slower speeds, increased energy expenditure, and reduced push-off [12]. The majority of previous studies have focused on magnitude of propulsion, moment, or power and often ignore the timing of these variables during the gait cycle. Magnitude-related measures, such as peak AGRF or ankle power, increase or modulate when walking at faster speeds, uphill, or against resistance [14,18]. Altered timing of propulsion has been found to restrain metabolic and mechanical efficiency in simulations and exoskeletons [11,41]. Modulation of timing of push-off in exoskeletons can help reduce net metabolic cost of walking [41]. In a recent detailed analysis of the timing of propulsion during gait in able-bodied individuals, Kuhman and Hurt showed that the timing of joint level locomotor propulsion relative to contralateral initial contact is modulated at different speeds [31]. However, if and how stroke affects the timing of propulsion is unknown. Thus, the objective of this study was to evaluate whether stroke affects the timing of peak propulsion and propulsion-related biomechanical variables with respect to ipsilateral toe-off.

Methods

Nine able-bodied (3 male, 6 female, age 24.0 ± 3.4 years) and 13 post-stroke (9 male, 4 female, age 60.1 ± 11.12 years, 38.5 ± 31.3 months post-stroke) individuals (Table – See Appendix) completed one gait analysis session. All participants provided informed consent approved by the Institutional Review Board. Due to lack of studies on propulsion timing in stroke, the sample size was based on effect size estimates and previous studies on propulsion magnitude [20].

After collecting demographic and clinical data (Table – see Appendix), reflective markers were attached to the pelvis, bilateral thigh, shank, and foot segments. Marker data were collected using a 7-camera motion capture system (Vicon Inc., Colorado, USA) at 100-Hz, and ground reaction force (GRF) data were captured using a split-belt instrumented treadmill at 1000-Hz (Bertec Inc., Columbus, Ohio, USA). Gait trials were collected at each participants' self-selected speed (1-min duration), determined after familiarization based on participant self-report during treadmill walking. During walking, participants held on to a front handrail (with instructions for and experimental monitoring of consistency of handrail support) and were provided an overhead safety harness without body-weight support for safety.

Labeled marker and GRF data were exported to Visual 3D (C-Motion Inc., Maryland, USA). The dependent variables were the timing of the peak amplitude of 4 variables during stance phase with respect to ipsilateral toe-off: AGRF, plantarflexor moment, ankle power, and ankle angle. One stroke participant did not show a positive AGRF peak (i.e. did not generate propulsion) during certain gait cycles; we included data from continuous gait cycles that did show AGRF for our analysis. Planned comparisons between the stroke participants' paretic versus non-paretic legs and the paretic leg of stroke participants versus the dominant leg of able-bodied participants were outlined a-priori. Independent sample t-tests were performed and Hedges' g effect sizes were calculated. Statistical significance was set at $p < .05$. All analyses were performed using SPSS Version 27.0 (IBM Corp., Armonk, NY, USA).

Results

We found a significantly earlier onset of peak AGRF (i.e. longer latency with respect to toe-off) for the stroke paretic leg versus stroke non-paretic leg (t(24) = 2.85, p = .009, Mdiff = 5.30, SE = 1.86, g = 1.08) and able-bodied individuals (t(14.31) = 6.26, p < .001, Mdiff = 9.01, SE = 1.44, g = 2.21) (Figure 6). The stroke paretic leg showed a significantly earlier onset of peak ankle plantarflexor moment versus able-bodied individuals (t(20) = 2.57, p = .018, Mdiff = 3.03, SE = 1.18, g = 1.07), but no difference versus the non-paretic leg (t(24) = 1.58, p = .128, Mdiff = 2.18, SE = 1.38, g = 0.60) (Figure 6). The stroke paretic leg displayed a significantly earlier onset of peak ankle power compared to the non-paretic leg (t(16.12) = 2.35, p = .032, Mdiff = 3.32, SE = 1.41, g = 0.89), and able-bodied individuals (t(13.31) = 2.55, p = .024, Mdiff = 3.40, SE = 1.34, g = 0.89) (Figure 6). No differences in timing of peak ankle angle were detected between paretic stroke leg and able-bodied (t(20) = 0.05, p = .958, Mdiff = 0.07, SE = 1.34, g = .02) or stroke non-paretic leg (t(24) = 0.27, p = .791, Mdiff = 0.37, SE = 1.39, g = 0.10).

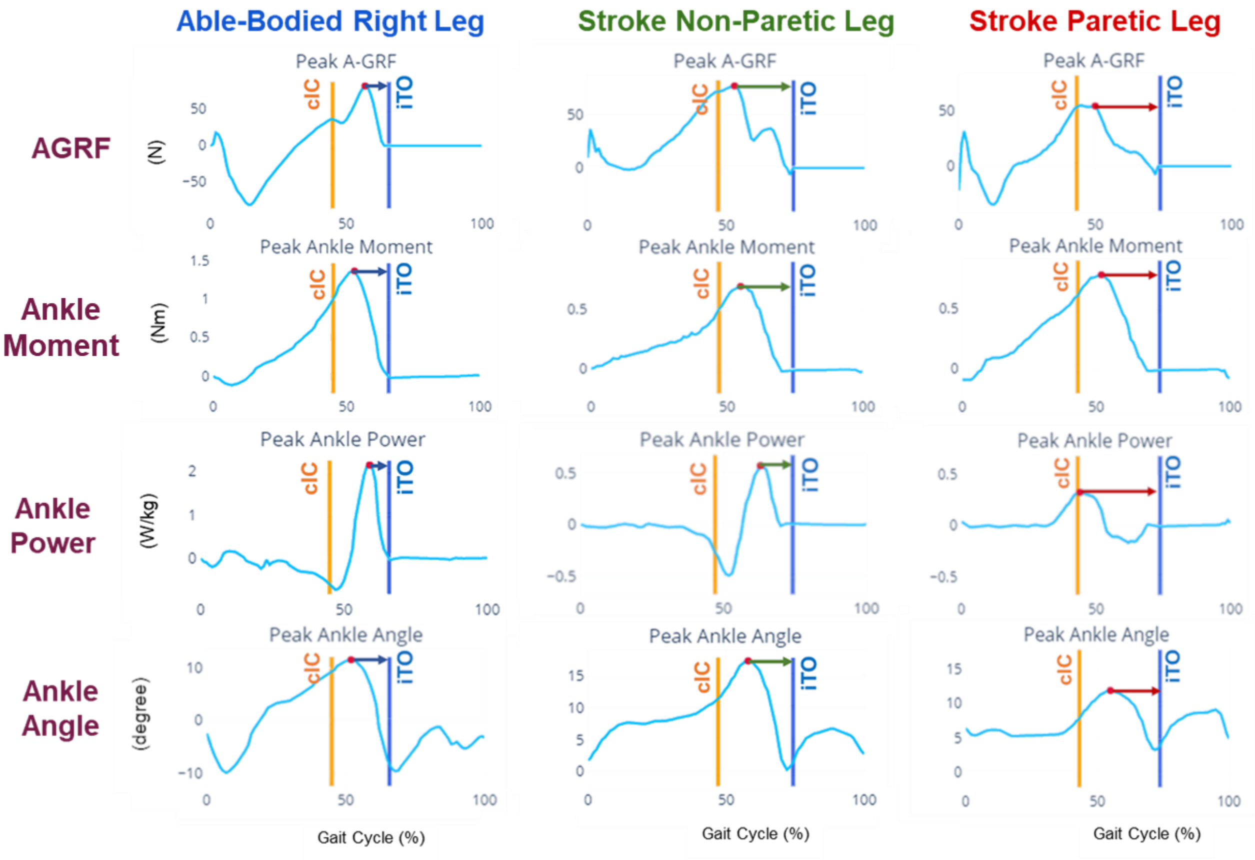


Figure 5. Representative time-normalized data (% gait cycle) of the 4 timing-related dependent variables. *The yellow vertical line represents contralateral initial contact (cIC) and the blue vertical line represents ipsilateral toe-off (iTO). The timing of the peak for each variable (red dot), as well as the latency of the peak from toe-off are indicated with an arrow. Note that the able-bodied right leg and non-paretic leg show more similarity in the timing of these variables except for peak AGRF. Note that compared to non-paretic and able-bodied legs, the paretic leg's generation of peak AGRF, peak moment, and peak power occur much earlier in the % gait cycle, i.e. with a longer latency with respect to ipsilateral toe-off (iTO). This figure is adapted from Alam et al, Gait & Posture (In Review).*

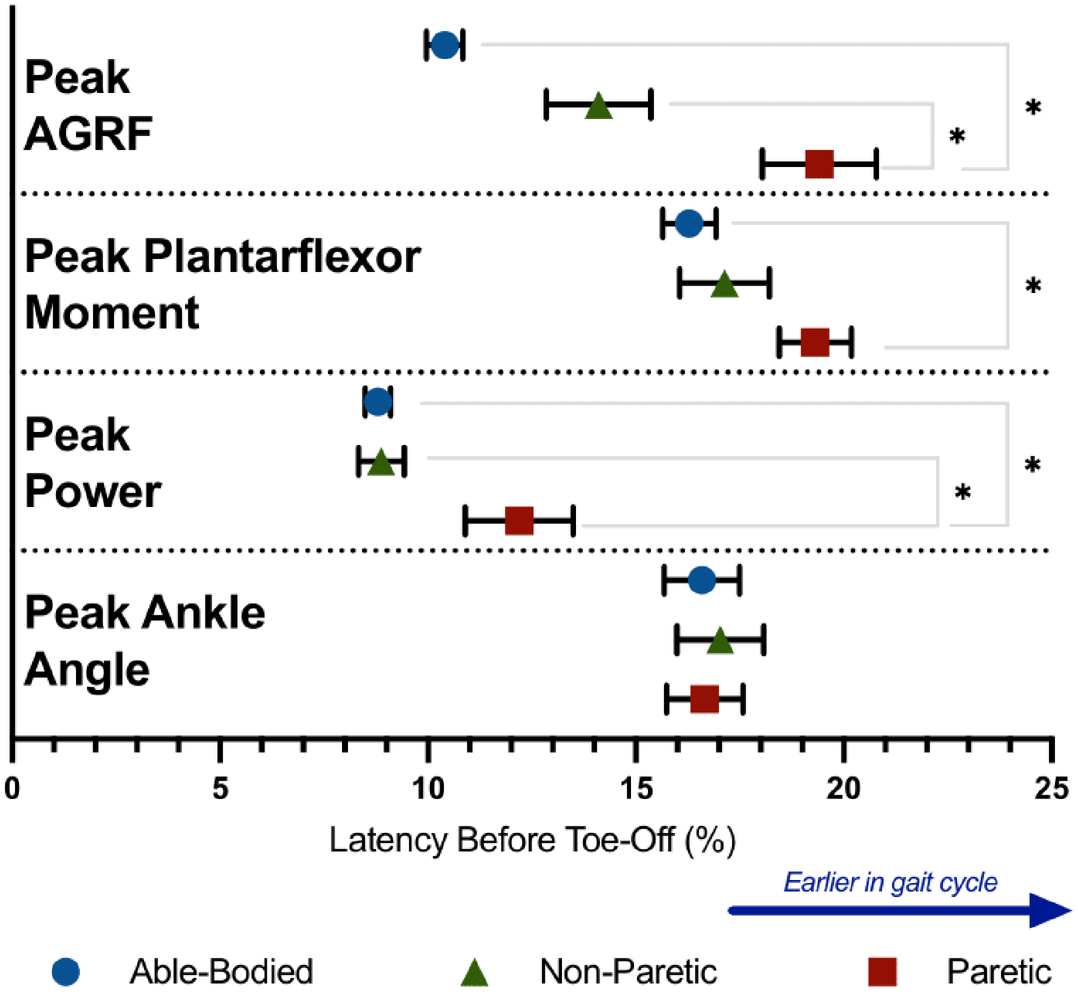


Figure 6. Group data (means with standard error bars) for the 4 timing-related variables for 13 post-stroke (paretic leg and non-paretic leg) and 9 able-bodied participants. *The x-axis shows latency or time of the peak of each variable with respect to ipsilateral toe-off in % gait cycle. Note that a larger latency indicates a longer delay between the peak generation and ipsilateral toe-off. Significant differences are indicated using symbols (*). This figure is adapted from Alam et al, Gait & Posture (In Review).*

Discussion

Our study demonstrates earlier timing of the peak AGRF in the paretic leg of stroke survivors compared to the stroke non-paretic leg and compared to able-bodied individuals. Stroke participants also demonstrated earlier timing of peak ankle power and earlier timing of peak ankle moment for the stroke paretic leg compared to able-bodied participants and the non-paretic leg.

In the stroke paretic leg, paretic peak AGRF was generated earlier with respect to toe-off compared to able-bodied individuals and their non-paretic leg peak AGRFs. Studies on unimpaired gait suggest that appropriate timing of propulsion helps optimize metabolic efficiency, walking consistency, and reduces the need for excessive hip torque to drive the center of mass forward during gait [32]. Timing of peak propulsion has less variation across walking speeds in able-bodied individuals, suggesting tighter neural control over this timing [31]. Deficits in descending neural drive, plantarflexor muscle activation, and power generation caused by aging [42] and stroke (as shown here) may result in diminished control over the timing of peak propulsion.

Additionally, propulsion-related variables, i.e. paretic peak power and peak moment also showed earlier onset compared to able-bodied and non-paretic peak power and able-bodied peak moment. Weakness of plantarflexor muscles caused by stroke coupled with subsequent deconditioning and atrophy may contribute to reduced magnitudes of peak plantarflexor moment and power [1], preventing plantarflexor muscles from maintaining sustained and rapid contractions needed for the steep rise and appropriate timing of propulsion during stance. Furthermore, inappropriate foot position during double limb-support and inadequate hip extension may also contribute to abnormal timing of propulsion and propulsion-related variables [8].

The limitations of our short report study include a relatively small sample size, use of handrail during gait for safety, determination of gait speed on the treadmill and not matched to overground speed, and collection of only treadmill and not overground gait data. Additional limitations include comparing the stroke paretic leg to only the dominant leg of able-bodied and potential effects of normalizing the timing data by stride versus stance. Future studies should extend our findings to a larger sample size, parse out the effects of leg dominance and side affected by stroke, and comprehensively evaluate relationships of these timing abnormalities to other post-stroke gait impairments and clinical outcomes of walking function. More testing conditions (e.g. range of speeds, biofeedback) can elucidate mechanisms of these timing abnormalities. Future studies are also warranted to explore the use of biofeedback and other post-stroke gait training strategies to normalize the timing of peak propulsion.

In conclusion, this brief report demonstrated an earlier onset of peak AGRF, peak ankle power, and peak ankle moment (with respect to toe off) during the gait cycle in the post-stroke participants' paretic leg compared to the non-paretic leg and able-bodied individuals. These abnormalities in the timing of propulsion-related variables may be an important, under-studied biomechanical mechanism underlying stroke gait impairments, and a promising therapeutic target for stroke gait retraining.

2.2. The Effect of Propulsion Biofeedback on the Timing of Propulsion-Related Biomechanical Variables.

Introduction

Propulsion, measured as anteriorly-directed ground reaction force (AGRF), is a crucial component of the gait cycle, which facilitates a smooth stance-to-swing transition [44] Ankle plantarflexor (PF) moment, ankle power generation, and ankle kinematics during mid- to late stance contribute to propulsive force generation. Clinical populations, such as individuals with chronic post-stroke hemiparesis, display reduced paretic propulsion and deviations in propulsion-related biomechanical variables [3]. These aberrant gait patterns adversely impact gait speed, gait symmetry, and walking function [3]. Gait interventions such as treadmill training, functional electrical stimulation, and gait biofeedback have shown improvements in AGRF [20,49]. Gait biofeedback (BF) provides the user with instantaneous, quantitative information regarding a targeted gait variable with the intent to improve gait impairments. Previous investigations demonstrate a change in magnitude of AGRF, PF moment, ankle power, and ankle angle with the use of AGRF-BF [20,49]; however, timing of these propulsion-related variables has largely been ignored. Altered propulsion timing has been found to restrain metabolic and mechanical efficiency in simulations and exoskeletons [11,41]. Though the timing of joint level locomotor propulsion is modulated at different speeds [31], the effect of AGRF-BF on the timing of propulsion-related variables is unknown. The purpose of this study was to examine the timing of propulsion-related biomechanical variables on BF-induced increases in AGRF in able-bodied individuals.

Methods

Baseline gait data were collected on a pilot sample of 5 healthy, able-bodied individuals (1 M, 4 F, 24.6 ± 2.5 y, 71.0 ± 5.8 kg) as they walked at a self-selected pace on an instrumented treadmill (Baseline). Next, during a BF trial at a matched speed (AGRF-BF), participants were provided audiovisual feedback to increase peak AGRF in the dominant leg by 25% compared to baseline [20,49]. Gait biomechanics data were collected with (AGRF-BF) and without (Baseline) AGRF biofeedback and normalized to percent stride. Dependent variables included (1) peak AGRF, (2) peak PF moment, (3) peak ankle power, and (4) peak dorsiflexion angle during the stance phase of gait. The timing of dependent variables was calculated as the latency with respect to ipsilateral toe-off, and the peak magnitude of each variable was identified. Paired samples t-tests were calculated to examine the effects of AGRF-BF on the timing and magnitude of propulsion-related dependent variables.

Results

As intended, BF targeting AGRF successfully increased peak AGRF during stance (Mdiff = 38.3 N, SE = 15.5, p = .034). AGRFBF did not impact the timing of peak AGRF (p = .236), peak dorsiflexion angle (p = .568), or peak PF moment (p = .342). Peak ankle power occurred significantly later in the gait cycle (Mdiff = 3.5, SE = 1.1, p = .037) with AGRF-BF, and there was a trend for an increase in the magnitude of peak ankle power (Mdiff = 0.46 W×kg-1 , SE.= 0.20, p = 0.82) (Figure 7).

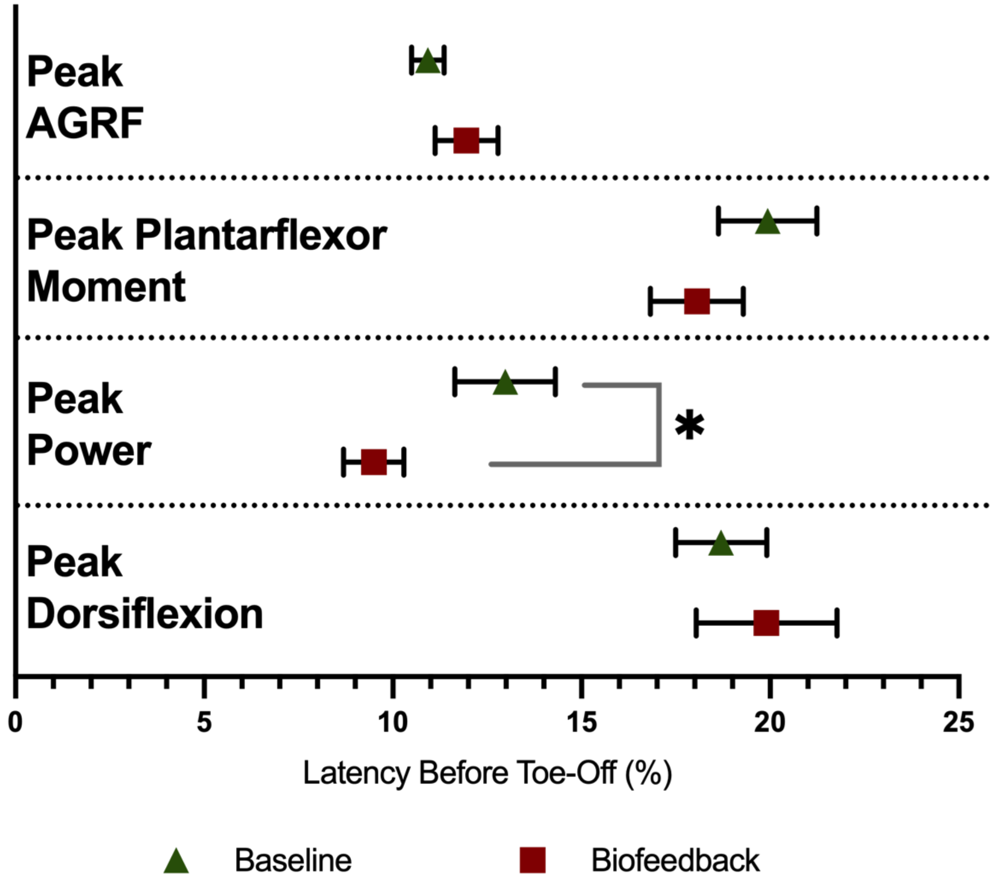


Figure 7. Mean ± SE of the 4 timing-related dependent variables during baseline and audiovisual biofeedback (Motion Monitor) of able-bodied individuals*. The x-axis displays latency or the time of the peak of each variable with respect to ipsilateral toe-off in % gait cycle. Larger latency indicates longer delay between peak generation and ipsilateral toe-off, i.e. earlier in the gait cycle. Significant difference between Baseline and Biofeedback trials are indicated using symbols (*).*

Discussion

As aforementioned, timing of peak propulsion in able-bodied individuals displays less variation across walking speeds suggesting tightly regulated neural control, which could explain the minimal effect of AGRF biofeedback on the timing of peak propulsion. However, reduced neural drive activation capacity [42] and weaker [1] plantarflexor muscles have been shown to reduce plantarflexor force generation. Thus, AGRF biofeedback may engage and motivate the participant to increase plantarflexor activation and consequently contractile force generation, thus increasing the magnitude of peak power and concomitantly shifting the timing of peak power to be closer to the end of the terminal double support stance phase.

Our results contribute to the investigation toward the possible effects of AGRF-BF on the timing of propulsion-related biomechanical variables. Future studies can explore translating AGRF biofeedback training to individuals with post-stroke hemiparesis. BF may be used to modulate the latency of the generation of propulsion-related biomechanical variables relative to toe-off. This study has potential implications for stroke gait rehabilitation, as normalization of timing may be a therapeutic target to enhance paretic propulsion and increase gait speed for post-stroke individuals.

2.3. The Effect of Different Modes of Biofeedback Interfaces on The Timing of Propulsion

Introduction

Our previous analysis demonstrates earlier timing of the peak AGRF in the paretic leg of stroke survivors compared to the stroke non-paretic leg and compared to able-bodied individuals. Stroke participants also demonstrated earlier timing of peak ankle power and earlier timing of peak ankle moment for the stroke paretic leg compared to able-bodied participants and the non-paretic leg. Excess negative collision work earlier in stance is detected in hemiparetic individuals [16]. Farris et. al found that the paretic limb contributes a higher percentage of negative work to each stride when compared to healthy control limbs. To counteract the greater negative work, greater positive work is generated from the hip and additionally redistributed to the hip from ankle joints, contributing to ankle immobility [16]. The greater collision work may be caused by limited stability and decreased ankle mobility of the leading paretic leg during initial contact, which could possibly disrupt ideal foot position and muscle activation for subsequent midstance and pre-swing, possibly affecting optimal timing.

Additionally, our lab's previous analysis demonstrated that propulsion biofeedback decreases latency of peak power relative to ipsilateral toe-off, but propulsion biofeedback did induce any changes in the timing of peak AGRF.

These findings contribute to the investigation toward the possible effects of AGRF biofeedback on the timing of propulsion-related biomechanical variables. However, one of our objectives was to explore translating AGRF biofeedback training to individuals with post-stroke hemiparesis. Biofeedback has implications in gait therapeutics as this method can potentially be used to modulate the latency of the generation of propulsion-related biomechanical variables relative to toe-off. Thus, the objective of this chapter was to explore the effect of video game biofeedback on the timing of propulsion. We hypothesized that the video game biofeedback (RockWalk) would shift the timing of peak AGRF closer to toe-off, thereby decreasing latency between the two gait events.

Methods

Three able-bodied participants (1 female, age 21.3 ± .58 y) and one post-stroke participant (69 y) completed a single-gait analysis session in the Motion Analysis Laboratory. All participants provided consent approved by the Institutional Review Board. Inclusion criteria included more than six months post-stroke, ability to complete one-minute continuous walking, and can communicate with the investigators. Exclusion criteria included neurologic diagnosis outside of stroke, hemineglect, cerebellar dysfunction, and orthopedic conditions that constrained walking function. Each participant was strapped with a heart rate monitor around their chest and a bio-signaling device around the pointer and middle finger of their left hand to measure physiological responses (heart rate and electrodermal activity; see Chapter 3) to biofeedback exposure.

Selection of Self-Selected Speed

Each participant initially walked on the split-belt treadmill to familiarize themselves with the lab environment. Afterwards, participants were instructed to walk on the treadmill, with the treadmill speed increased by 0.1 m/s increments until the participant reported their self-selected comfortable walking speed. Ground reaction force data were captured using force platforms embedded within a split-belt treadmill at 1000 Hz (Bertec Inc., Columbus, Ohio, USA). All successive trials were performed at self-selected speed and participants were provided support using an overhead safety harness as well as had a handrail to hold. Each participant was instructed to maintain a consistent grip on the handrail throughout each trial. Furthermore, if there were any visual cues that the participant possessed an excessive reliance on the handrail or excessive trunk lean to support their gait, then that particular gait trial was redone.

Control Trial and Calculating Target AGRF

Each participant completed a thirty second trial of normal walking, where their baseline AGRF was collected by the force platforms in the split-belt treadmill. The target AGRFs used for the modes of biofeedback for abled-bodied individuals were calculated to be 15% greater than their baseline AGRF of their dominant leg. Afterwards, able-bodied participants completed a sixty second control trial of baseline walking with no instruction.

On the contrary, the post-stroke individual first walked sixty seconds of baseline walking with no instruction. Based on the baseline AGRF from the control trial, five target AGRF values were generated (Equation 1) using paretic and non-paretic peak AGRFs measured during the baseline trial to set a challenging, individualized target AGRF for each participant. Inter-limb deficits are much greater in post-stroke individuals than able-bodied participants, and as a result, a target paretic AGRF that is not too challenging nor too easy relative to their non-paretic AGRF had to be selected.

$$\text{Target AGRF} = \text{Paretic AGRF} + n(\text{nonparetic AGRF} - \text{Paretic AGRF});$$

$$n = 0.2, 0.4, 0.6, 0.8, 1.0$$

After calculation of the five target AGRF values, the participant completed five brief thirty second trials at each target value. Thirty second trials were used to minimize fatigue. The participant received instruction on the target AGRF parameter and the first biofeedback interface that they were exposed to (Motion Monitor). Target AGRF selected for the subsequent biofeedback trials corresponded to the thirty second trial where the participant achieved the target greater than 50% of gait cycles. This target AGRF calculation method was used in a previous study in the lab [11].

Methodology of Basic Audiovisual Biofeedback (Motion Monitor)

Participants completed a sixty second trial where they were each exposed to the basic audiovisual biofeedback interface (Motion Monitor). Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 1). Visual biofeedback was presented with a horizontal line with a cursor (X) that represented the real-time generated paretic AGRF. The target AGRF was represented by a green line with a 6-Newton error tolerance range centered at the AGRF target. Audio biofeedback was relayed by an audio tone that played when AGRF produced reached the target range during each gait cycle, indicating success. The participant was instructed prior to the trial that the cursor represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to reach the target range. Instructions concerning strategies to increase AGRF were not given.

Methodology of Video Game Biofeedback (RockWalk)

Participants completed a sixty second trial where they were each exposed to video game biofeedback (RockWalk). RockWalk is a visual effects game designed for gait biofeedback and takes advantage of a high-definition graphical display in contrast to the simple, non-intuitive display seen in Motion Monitor. Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 2). Visual biofeedback was presented through visual animations within a gamified environment. An avatar was placed into the game, represented by a badger with a construction hat, to enhance the immersive experience of the game design and setting. The axe works in synchronously with the generation of paretic AGRF and moves accordingly to the force produced. When generated AGRF reaches target AGRF, the axe is visually animated to strike the crystal rock which is subsequently collected by a cart, rewarding the participant with an increased game score. Audio biofeedback is comprised of a clinking sound that plays when the crystal is stricken by the axe in addition to voice-acted reinforcing statements (“that was awesome,” “good job”) vocalized by the badger character in the game. After sixty seconds, the game ends and a table presenting the final game score is shown to the player. The participant was instructed prior to the trial that the axe represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to break the crystal rocks, indicating that target AGRF was reached. Instructions concerning strategies to increase AGRF were not given.

Engagement and Physiological Components

After completion of sixty second trials, the average heart rate collected by the heart rate monitor of each participant was recorded. Second, each participant's electrodermal activity (EDA) over the sixty second trial was collected. Third, each participant was asked for their rating of perceived exertion (RPE) of each trial, with six representing the lowest intensity and effort and twenty representing the highest intensity and effort (Appendix). Fourth, an engagement questionnaire was given to each participant. The questionnaire provided two polarizing adjectives with 1 representing the "negative" adjective and 7 representing the "positive" adjective. Whichever number that the participant marked represented the subjective experience and attitude of each biofeedback interface (Figure 10). The results of these collected data are presented in Chapter 3 of the thesis.

Dependent Variables and Data analysis

The primary dependent variable that was measured was peak AGRF produced of the dominant leg of able-bodied participants and the paretic and non-paretic limbs of post-stroke individuals. Collected GRF data from the split-belt treadmill were exported to Visual 3D. In Visual 3D, peak AGRF was calculated as the peak value of AGRF produced in terminal double support phase. After normalization to percent gait cycle, the timing of dependent variables was calculated as the latency of peak AGRF with respect to ipsilateral toe-off. Average peak AGRF latency relative to toe-off of able-bodied and post-stroke participants for each condition (no biofeedback, Motion Monitor, RockWalk) were calculated and analyzed. Additionally, coefficient of variance of the stride-to-stride latencies were calculated and analyzed.

Statistical Analysis

A one-way repeated measures ANOVA was conducted to evaluate the effect of the different modes of biofeedback (no biofeedback, Motion Monitor, RockWalk) on the dependent variable, which is timing of peak AGRF. If ANOVA showed a main effect, Bonferroni-corrected planned post-hoc paired comparisons were conducted to evaluate differences between no biofeedback and modes of biofeedback (Motion Monitor, RockWalk) as well as to evaluate differences between the modes of biofeedback. Significance level was set at $\alpha \leq 0.05$ for all tests. Measures of effect size in ANOVA were used to measure the degree of association between different modes of biofeedback on latency of peak AGRF to ipsilateral toe-off and stride-to-stride variability of peak AGRF timing.

Results

Timing of Peak AGRF of the targeted leg

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on the timing of peak AGRF of the targeted leg (p=

.582, F=.619) (Figure 8). However, there was a trend of a decrease in latency of peak AGRF to ipsilateral toe-off. The effect size of mode of biofeedback on latency of peak AGRF relative to ipsilateral toe-off was $\eta^2 = .23$, indicating a strong relationship between mode of biofeedback and latency of peak AGRF timing relative to ipsilateral toe-off.

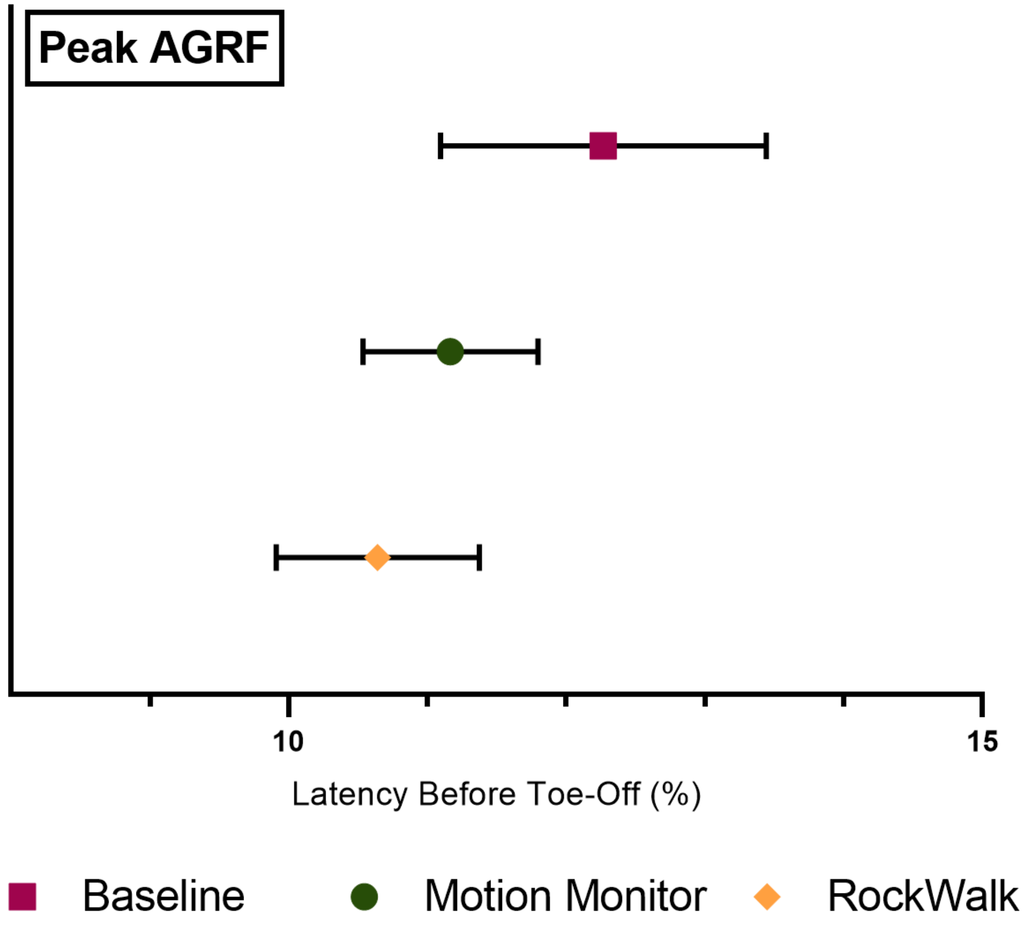


Figure 8. Mean ± SE of timing of peak AGRF of the targeted during baseline, conventional biofeedback interface (Motion Monitor), and video game biofeedback interface (RockWalk) of able-bodied individuals*. The x-axis displays latency or the time of the peak of each variable with respect to ipsilateral toe-off in % gait cycle. Larger latency indicates longer delay between peak generation and ipsilateral toe-off, i.e. earlier in the gait cycle. There is no significant main effect of biofeedback mode on timing of peak AGRF, though there is a decreasing trend of latency to ipsilateral toe-off****.***

Coefficient of Variance of the timing of Peak AGRF

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on the timing of peak AGRF of the targeted leg (p= .518, F=.77) (Figure 9). However, there was a decrease in stride-to-stride variability of the timing of peak AGRF relative to ipsilateral toe-off ($\eta^2 = .29$).

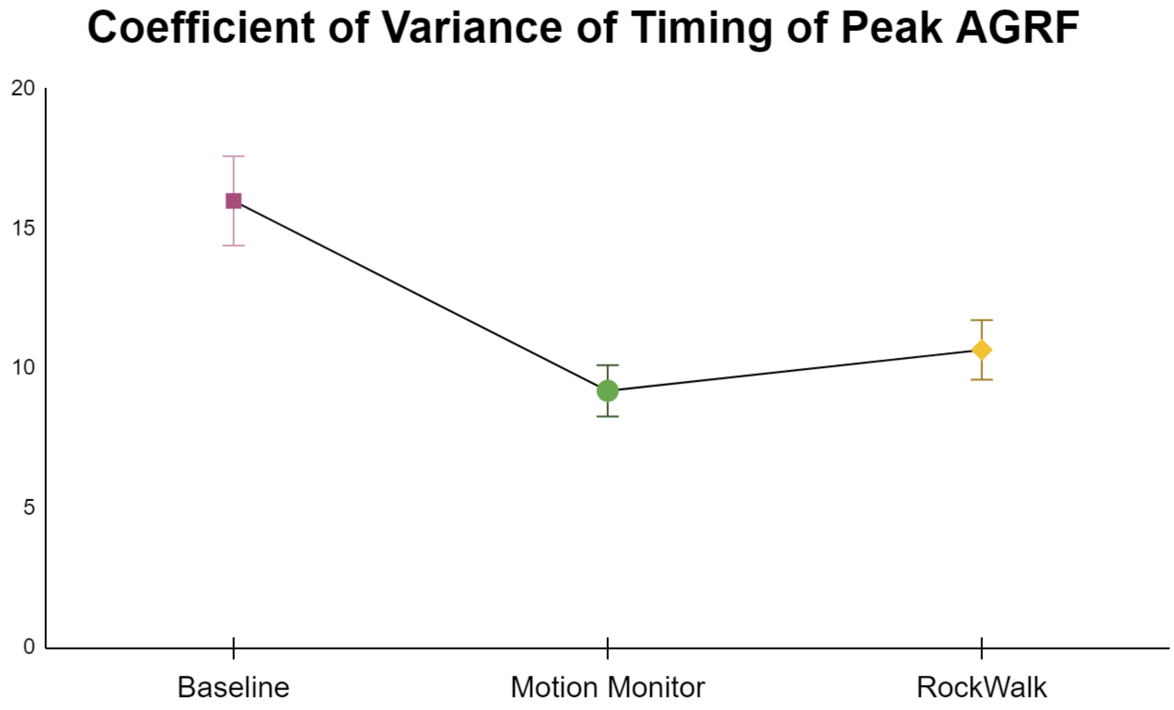


***Figure 9. Mean ± SE of stride-to-stride coefficient of variance (CoV) of peak AGRF timing of the targeted during baseline, conventional biofeedback interface (Motion Monitor), and video game biofeedback interface (RockWalk) gait trials of able-bodied individuals*.**

Discussion

Our preliminary results demonstrate that while there were changes in the timing of peak AGRF relative to ipsilateral toe-off after exposure to either conventional or video game biofeedback, these effects were not significant. We also showed a decrease in the stride-to-stride variability of the timing latencies of peak AGRF after exposure to both types of biofeedback.

Timing of peak propulsion in able-bodied individuals displays less variation across walking speeds suggesting tightly regulated neural control [31], which could explain the small effect of propulsion biofeedback on the timing of peak propulsion. Despite changes in walking conditions such as different walking speeds [31] or exposure to biofeedback, these preliminary results contribute to the growing evidence that the timing of peak AGRF may be consistently and tightly maintained to ensure efficient gait. Preliminary evidence from our current work suggests that the timing of peak AGRF in healthy individuals with respect to ipsilateral toe-off do not show significant changes with biofeedback, but future studies can evaluate if the timing of AGRF may modulate with greater dosages or practice durations with biofeedback. Hemiparetic post-stroke individuals have demonstrated earlier timing of their peak AGRF in the gait cycle, illustrated by their greater latencies of peak AGRF from toe-off. Through our preliminary results, we see a slight shift of peak AGRF closer to toe-off after exposure to Motion Monitor and RockWalk, with RockWalk having the greatest effect, as we hypothesized. These preliminary results are additionally limited by brief exposure time (sixty seconds) and only a single-session trial, and while they show promising effects for the potential of biofeedback for shifting peak AGRF closer to ipsilateral toe-off post-stroke, larger-sample studies may be needed to evaluate this systematically. It may be possible that biofeedback would be induce an even larger effect on the timing of peak AGRF with multiple training sessions and longer training bouts, which warrants the need for future studies to explore these conditions.

Moreover, there was a trend for stride-to-stride variability of the timing of peak AGRF relative to ipsilateral toe-off to decrease during the biofeedback walking trials. Our preliminary results demonstrate that exposure to both conventional and video game biofeedback decreases the variability of timing of peak AGRF within the gait cycle. Thus, potentially, propulsion biofeedback may not only shift the timing of peak AGRF closer to toe-off, but also induce greater stride-to-stride consistency in the timing of peak AGRF. These results may relate to the possible importance of the role of a tight neural control of the timing of peak AGRF in maintaining healthy gait patterns. Stroke often leads to deficits in descending neural drive of the paretic side [26], possibly damaging the rigid neural control over timing of peak AGRF of the paretic limb. Thus, there may be a therapeutic need in gait retraining to restore proper neural control of the timing of and not just the magnitude of paretic peak AGRF, and propulsion biofeedback may play a role in reducing variability of the timing of peak AGRF. Therefore, there is a need for further studies to investigate into the variability of the timing of peak AGRF in post-stroke participants as well as the possible use of therapeutic measures such as propulsion biofeedback in rehabilitating descending neural control of both propulsion magnitude and timing.

3. THE EFFECT OF DIFFERENT MODES OF BIOFEEDBACK INTERFACE ON AROUSAL STATE AND ENGAGEMENT

Introduction

“Gamification” is the incorporation of game-based elements such as point-scoring and competition with others in non-game-based activities. The objective of gamification is to augment user engagement and motivation with the product or activity. Thus, translating game-based elements into traditional rehabilitation tasks may have potential implications in creating a more engaging and motivating training session, and may help to distract from fatigue or boredom. Currently, intuitive and engaging games designed for specific gait deficits are not available in rehabilitation clinics.

Previous studies have explored the effect of game-based therapy on rehabilitation efficacy. A Nintendo Wii video game was implemented into a familiar task of treadmill walking or cycling, which led to an increase in exercise intensity (heart rate, cadence, speed) during training [15,19]. Moreover, video game therapy resulted in improvements for mobility, selective attention, and balance in people with chronic traumatic brain injury in comparison to traditional balance platform therapy [52]. In frail, community-dwelling older adults, dynamic balance exercises coupled to interactive game-based exercise induced improvements in balance control [54]. Commercially available video game systems such as the Nintendo Wii [48,55] and Kinect [35] have been incorporated into rehabilitative strategies and have shown to increase enjoyment during therapy sessions in individuals with disabilities. When video games were used for upper-limb rehabilitation, users relayed that the game made rehabilitation more entertaining and helped achieve greater exercise intensity [34].

Exercise intensity and engagement level can be assessed physiologically through the arousal state and heart rate [22] of the user. Arousal state has been previously measured by assessing electrodermal activity [24,28]. Electrodermal activity (EDA) is the measurement of skin conductance through the attachment of two-electrodes to the user's skin and is considered to be a reliable marker of sympathetic nervous system arousal [7]. Sympathetic arousal induces changes in sweat gland activity, which indicate changes in attention levels and emotional states [7]. Furthermore, EDA changes regulates responses to internal and external stimuli [24] . EDA is commonly used to evaluate response to stimuli and is therefore commonly used as an assessment tool to measure user engagement [24,28].

Our objective is that post-stroke individuals demonstrate greater engagement, motivation, and therapeutic benefits during gait training sessions involving biofeedback when training incorporates intuitive, entertaining, game-based interfaces. By making gait training appealing and meaningful, patients are encouraged to engage in adequate repetitions, intensity, and challenge to maximize therapeutic effectiveness. Thus, we hypothesize video game biofeedback (RockWalk) will be the most engaging mode of biofeedback and induce the highest exercise intensity.

Methods

Three able-bodied participants (1 female, age 21.3 ± .58 y) and one post-stroke individual (69 y) completed a single-gait analysis session in the Motion Analysis Laboratory. All participants provided consent approved by the Institutional Review Board. Inclusion criteria included more than six months post-stroke, ability to complete one-minute continuous walking, and can communicate with the investigators. Exclusion criteria included neurologic diagnosis outside of stroke, hemineglect, cerebellar dysfunction, and orthopedic conditions that constrained walking function. Each participant was strapped with a heart rate monitor around their chest and a bio-signaling device around the pointer and middle finger of their left hand to measure physiological responses (heart rate and EDA) to biofeedback exposure

Selection of Self-Selected Speed

Each participant initially walked on the split-belt treadmill to familiarize themselves with the lab environment. Afterwards, participants were instructed to walk on the treadmill, with the treadmill speed increased by 0.1 m/s increments until the participant reported their self-selected comfortable walking speed. Ground reaction force data were captured using force platforms embedded within a split-belt treadmill at 1000 Hz (Bertec Inc., Columbus, Ohio, USA). All successive trials were performed at self-selected speed and participants were provided support using an overhead safety harness as well as had a handrail to hold. Each participant was instructed to maintain a consistent grip on the handrail throughout each trial. Furthermore, if there were any visual cues that the participant possessed an excessive reliance on the handrail or excessive trunk lean to support their gait, then that particular gait trial was redone.

Control Trial and Calculating Target AGRF

Each participant completed a thirty second trial of normal walking, where their baseline AGRF was collected by the force platforms in the split-belt treadmill. The target AGRFs used for the modes of biofeedback for abled-bodied individuals were calculated to be 15% greater than their baseline AGRF of their dominant leg. Afterwards, able-bodied participants completed a sixty second control trial of baseline walking with no instruction.

On the contrary, the post-stroke individual first walked sixty seconds of baseline walking with no instruction. Based on the baseline AGRF from the control trial, five target AGRF values were generated (Equation 1) using paretic and non-paretic peak AGRFs measured during the baseline trial to set a challenging, individualized target AGRF for each participant. Inter-limb deficits are much greater in post-stroke individuals than able-bodied participants, and as a result, a target paretic AGRF that is not too challenging nor too easy relative to their non-paretic AGRF had to be selected.

$$\text{Target AGRF} = \text{Paretic AGRF} + n(\text{nonparetic AGRF} - \text{Paretic AGRF});$$

$$n = 0.2, 0.4, 0.6, 0.8, 1.0$$

After calculation of the five target AGRF values, the participant completed five brief thirty second trials at each target value. Thirty second trials were used to minimize fatigue. The participant received instruction on the target AGRF parameter and the first biofeedback interface that they were exposed to (Motion Monitor). Target AGRF selected for the subsequent biofeedback trials corresponded to the thirty second trial where the participant achieved the target greater than 50% of gait cycles. This target AGRF calculation method was used in a previous study in the lab [11].

Methodology of Basic Audiovisual Biofeedback (Motion Monitor)

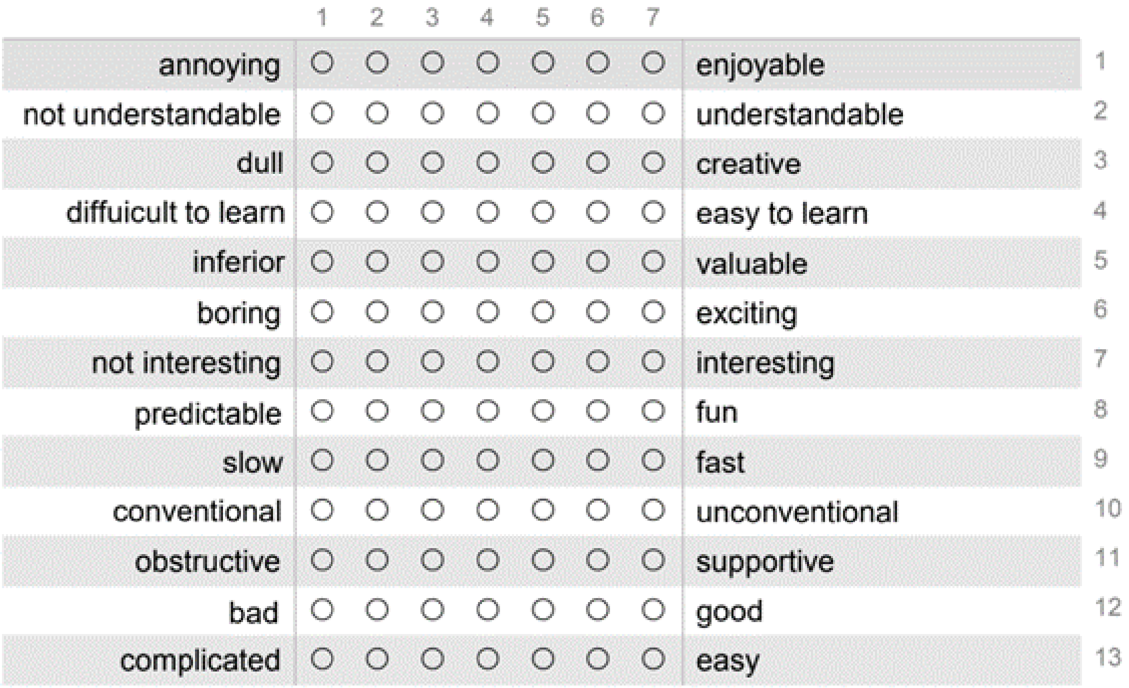
Participants completed a sixty second trial where they were each exposed to the basic audiovisual biofeedback interface (Motion Monitor). Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 1). Visual biofeedback was presented with a horizontal line with a cursor (X) that represented the real-time generated paretic AGRF. The target AGRF was represented by a green line with a 6-Newton error tolerance range centered at the AGRF target. Audio biofeedback was relayed by an audio tone that played when AGRF produced reached the target range during each gait cycle, indicating success. The participant was instructed prior to the trial that the cursor represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to reach the target range. Instructions concerning strategies to increase AGRF were not given.

Methodology of Video Game Biofeedback (RockWalk)

Participants completed a sixty second trial where they were each exposed to video game biofeedback (RockWalk). RockWalk is a visual effects game designed for gait biofeedback and takes advantage of a high-definition graphical display in contrast to the simple, non-intuitive display seen in Motion Monitor. Visual and auditory biofeedback were relayed on a screen placed in front of the participant and a speaker (Figure 2). Visual biofeedback was presented through visual animations within a gamified environment. An avatar was placed into the game, represented by a badger with a construction hat, to enhance the immersive experience of the game design and setting. The axe works in synchronously with the generation of paretic AGRF and moves accordingly to the force produced. When generated AGRF reaches target AGRF, the axe is visually animated to strike the crystal rock which is subsequently collected by a cart, rewarding the participant with an increased game score. Audio biofeedback is comprised of a clinking sound that plays when the crystal is stricken by the axe in addition to voice-acted reinforcing statements (“that was awesome,” “good job”) vocalized by the badger character in the game. After sixty seconds, the game ends and a table presenting the final game score is shown to the player. The participant was instructed prior to the trial that the axe represented how hard they were pushing the ground backward with their paretic foot, and the objective was to push-off harder with the paretic leg to break the crystal rocks, indicating that target AGRF was reached. Instructions concerning strategies to increase AGRF were not given.

Engagement and Physiological Components

After completion of sixty second trials, the average heart rate collected by the heart rate monitor of each participant was recorded. Second, each participant's EDA over the sixty second trial was collected. Third, each participant was asked for their rating of perceived exertion (RPE) of each trial, with six representing the lowest intensity and effort and twenty representing the highest intensity and effort (Appendix). Fourth, an engagement questionnaire was given to each participant. The questionnaire provided two polarizing adjectives with 1 representing the "negative" adjective and 5 representing the "positive" adjective. Whichever number that the participant marked represented the subjective experience and attitude of each biofeedback interface (Figure 10).



	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
dull	○	○	○	○	○	○	○	creative	3
diffuicult to learn	○	○	○	○	○	○	○	easy to learn	4
inferior	○	○	○	○	○	○	○	valuable	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
predictable	○	○	○	○	○	○	○	fun	8
slow	○	○	○	○	○	○	○	fast	9
conventional	○	○	○	○	○	○	○	unconventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
bad	○	○	○	○	○	○	○	good	12
complicated	○	○	○	○	○	○	○	easy	13

Figure 10. Screenshot of engagement questionnaire. *Thirteen opposing adjectives are presented within the questionnaire. Each participant was asked to mark the bubble that was closest to the adjective that subjectively matched their views on the mode of biofeedback (no biofeedback, Motion Monitor, RockWalk). 1 represents the "negative" adjective and 7 represents the "positive" adjective.*

Dependent Variables and Data analysis

The primary dependent variables that were measured were average heart rate, average RPE, average engagement questionnaire scores, and skin conductance response (SCR) in response to different biofeedback conditions (no biofeedback, Motion Monitor, RockWalk). Skin conductance response is calculated from raw EDA signal and is an indicator of nonspecific physiological response or to a specific stimulus in the game. Features of SCR such as SCR mean amplitude have been correlated to cognitive load, attention, and affective states [7,24,46]. Raw EDA data, after conversion from Volts to Siemens, was exported to MATLAB, where a low-pass Butterworth filter was used to remove components of EDA that is minimally correlated to arousal state [7,24] and minimize movement artifacts. Peak detection was performed on the remaining waveform, with the minimum peak amplitude set at .01 uS to eliminate more movement artifacts and non-SCR noise. Mean SCR amplitude was collected. Additionally, heart rate, RPE, and questionnaire scores were collected, and mean data and standard deviation were calculated.

Statistical Analysis

A one-way repeated measures ANOVA was conducted to evaluate the effect of the different modes of biofeedback (no biofeedback, Motion Monitor, RockWalk) on the dependent variables, which are heart rate, SCR, and RPE. If ANOVA showed a main effect, Bonferroni-corrected planned post-hoc paired comparisons were conducted to evaluate differences between no biofeedback and modes of biofeedback (Motion Monitor, RockWalk) as well as to evaluate differences between the modes of biofeedback. Significance level was set at $\alpha \leq 0.05$ for all tests.

Measures of effect size in ANOVA were used to measure the degree of association between different modes of biofeedback on SCR mean amplitude, average heart rate, and RPE. Descriptive statistics were used to compare the engagement rating between basic interface biofeedback and video game biofeedback trials.

Results

Skin Conductance Response

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed no significant main effect of biofeedback mode on skin conductance response mean amplitude (p= .135, F=3.43) (Figure 12). However, there was a trend for increase in SCR mean amplitude with biofeedback (effect size $\eta^2 = .63$).

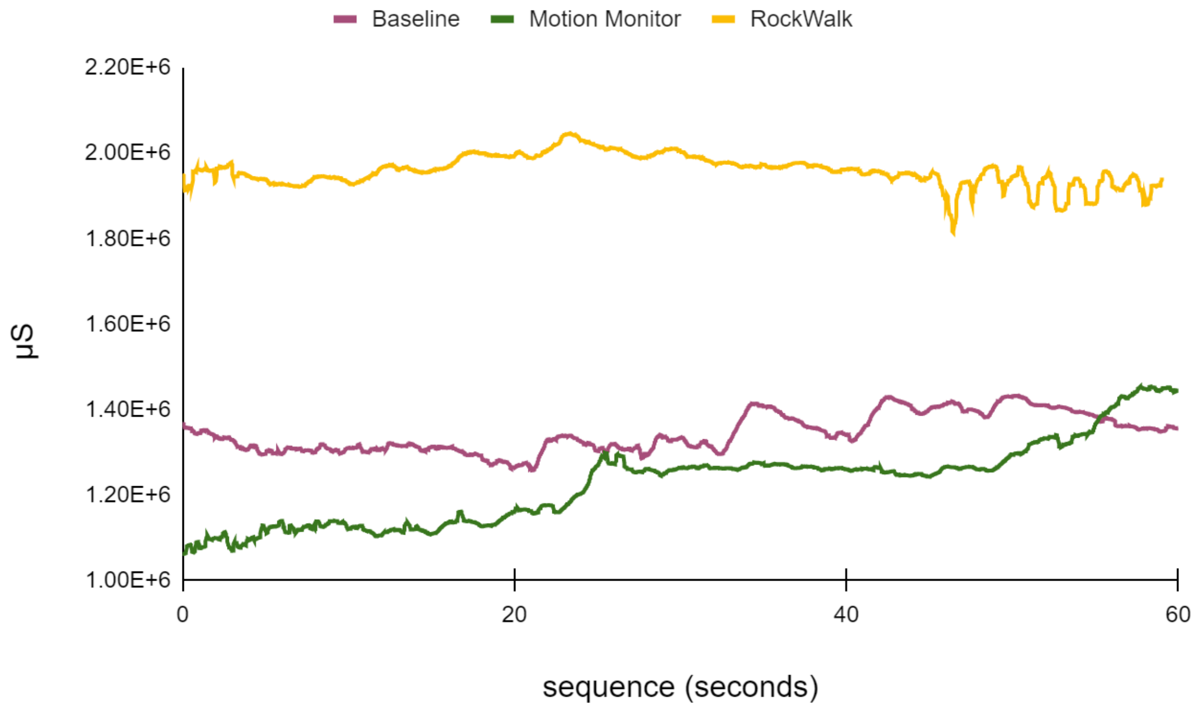


Figure 11. Raw representative data of EDA signals (µS or micro-Siemens) of one able-bodied participant.

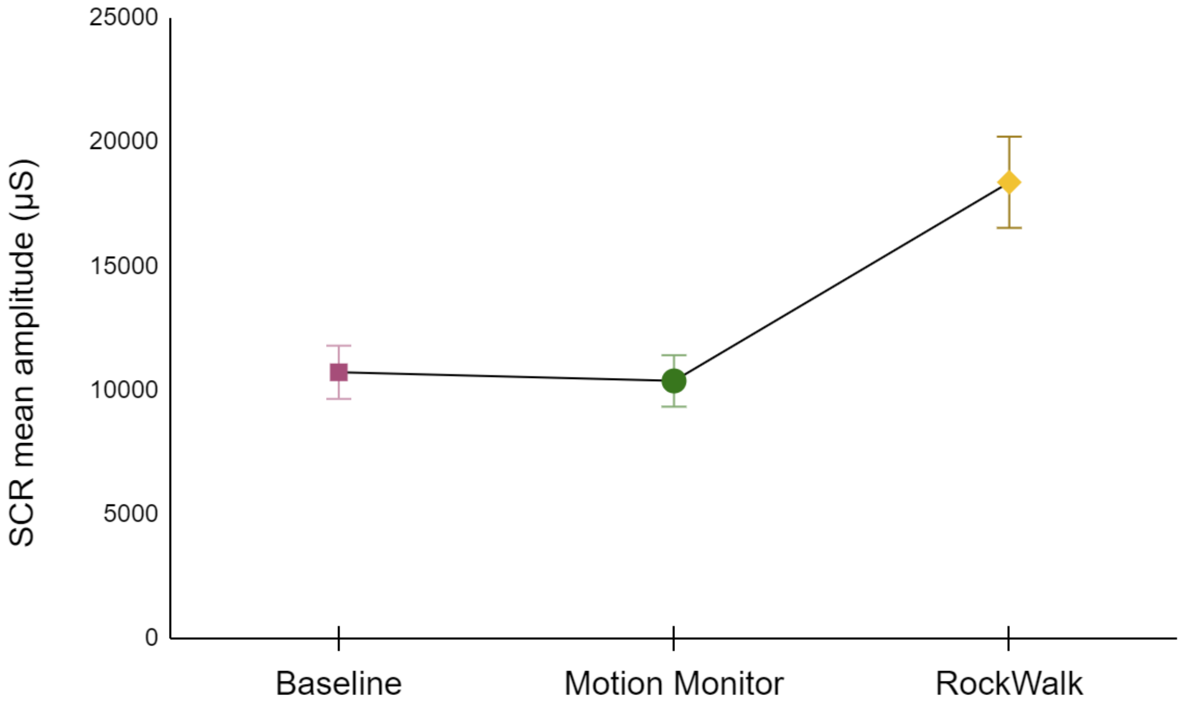


Figure 12. Mean ± SE Skin conductance response amplitude (µS) of able-bodied participants exposed to different modes of biofeedback.

Heart Rate

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed significant main effect of biofeedback mode on heart rate (p= .02, F=11.42) (Figure 13). Bonferroni-corrected post hoc paired comparisons showed significantly greater average heart rated induced by video game biofeedback (RockWalk) compared to no biofeedback (p=.003). There was no significant difference in average heart rate found between basic interface biofeedback (Motion Monitor) and no biofeedback (p=.08) and there was no significant difference found between the two modes of biofeedback (Motion Monitor, RockWalk) (p=.57). Additionally, Motion Monitor induced a 5.03% increase in average heart rate from baseline while RockWalk induced a 6.19% increase in average heart rate from baseline (Figure 14). Lastly, the effect size of mode of biofeedback on average heart rate was $\eta^2 = .85$, indicating a very strong relationship between mode of biofeedback and average heart rate.

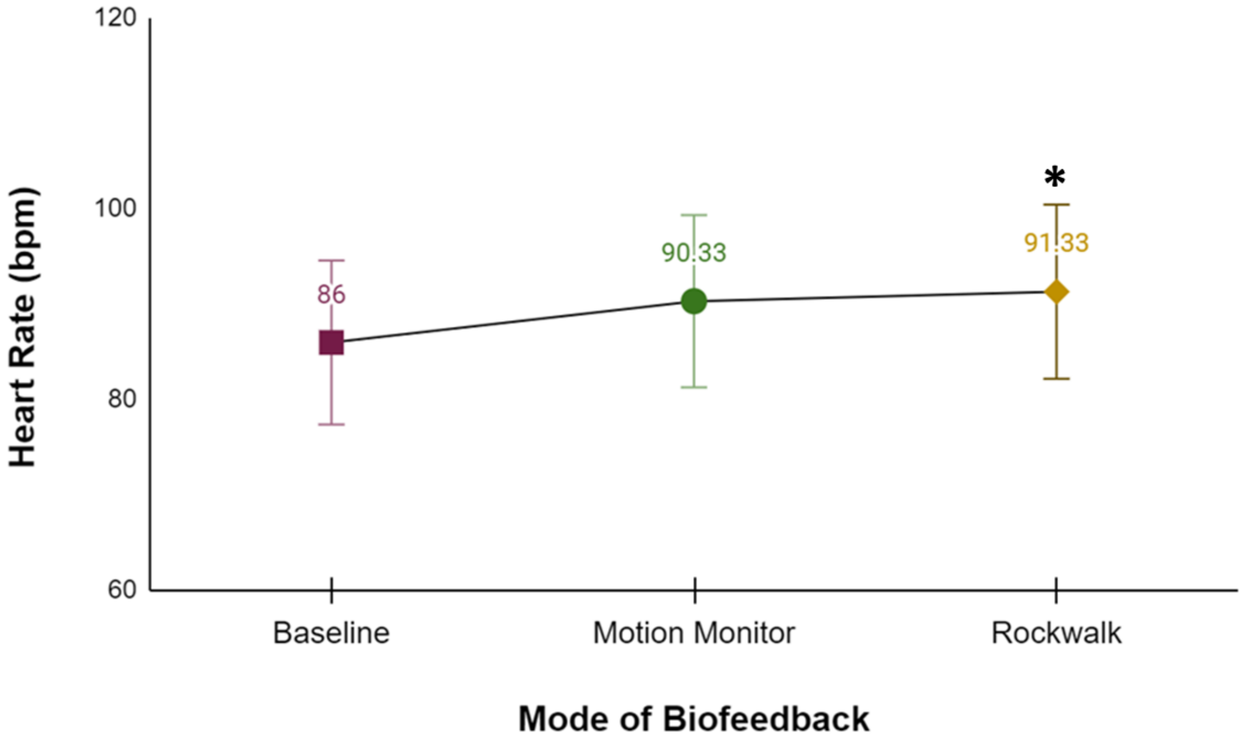


Figure 13. Mean ± SE heart rate (bpm) of able-bodied participants exposed to different modes of biofeedback. *The * indicates significant difference from the no biofeedback, or baseline, condition.*

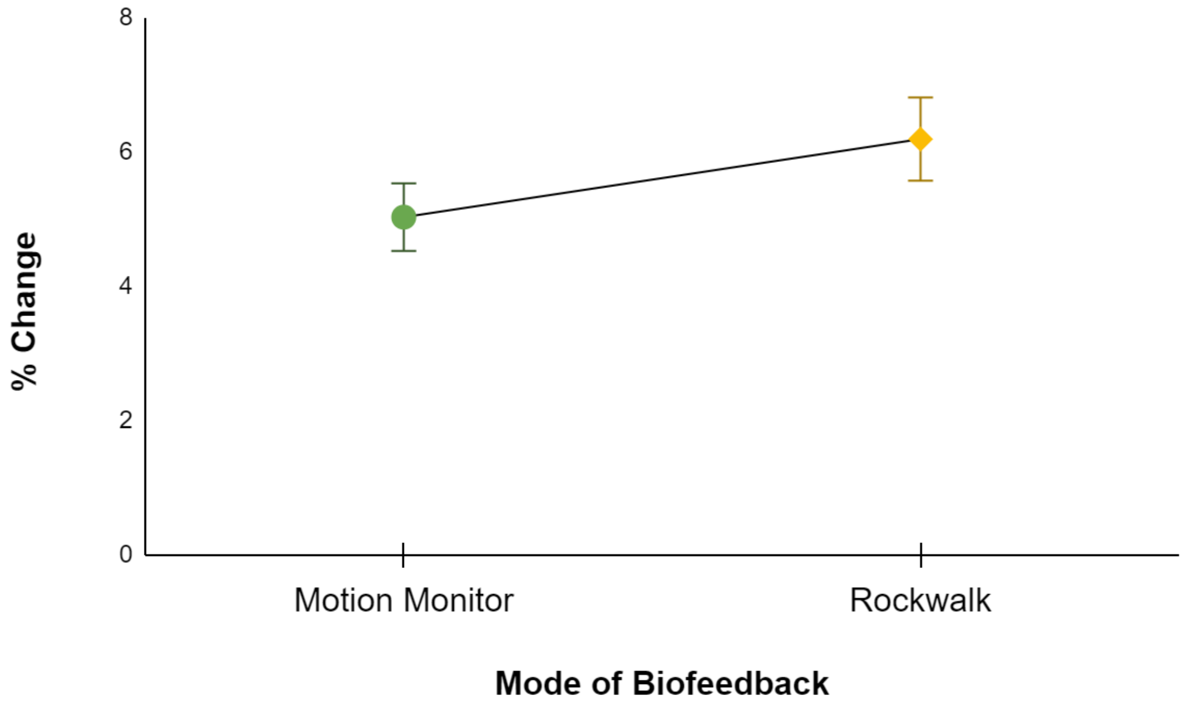


Figure 14. Percent change of average HR of able-bodied participants exposed to different modes of biofeedback from baseline.

Rating of Perceived Exertion

The one-way repeated measures ANOVA evaluating the effect of biofeedback showed significant main effect of biofeedback mode on RPE ($p=.006$, $F=22.7$)(Figure 15). Bonferroni-corrected post hoc paired comparisons showed significantly greater average RPE induced by video game biofeedback (RockWalk) compared to no biofeedback ($p=.008$). There was no significant difference in average RPE found between basic interface biofeedback (Motion Monitor) and no biofeedback ($p=.12$) and there was no significant difference found between the two modes of biofeedback (Motion Monitor, RockWalk) ($p=.07$). . Motion Monitor induced a 20.75% increase in average RPE from baseline while RockWalk induced a 45.75% increase in average RPE from baseline (Figure 16). Lastly, the effect size of mode of biofeedback on average RPE was $\eta^2 = .91$, indicating a very strong relationship between mode of biofeedback and average RPE.

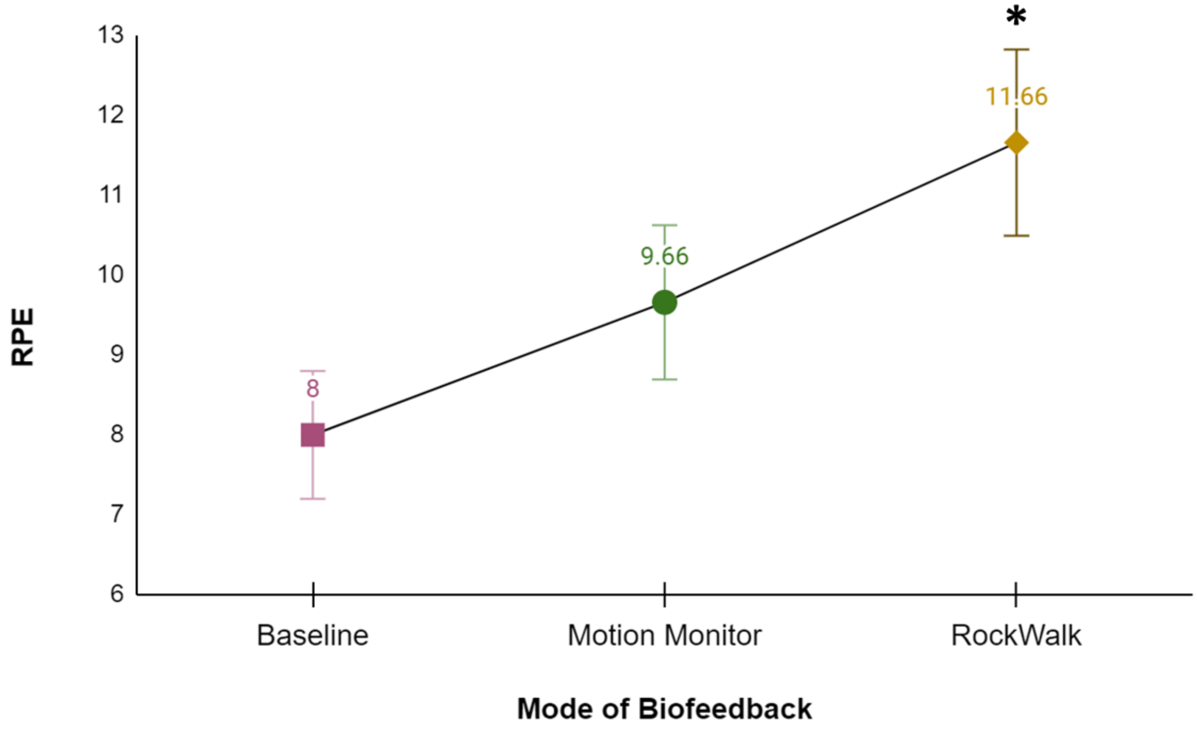


Figure 15. Mean ± SE RPE of able-bodied participants exposed to different modes of biofeedback. *The * indicates significant difference from the no biofeedback, or baseline, condition.*

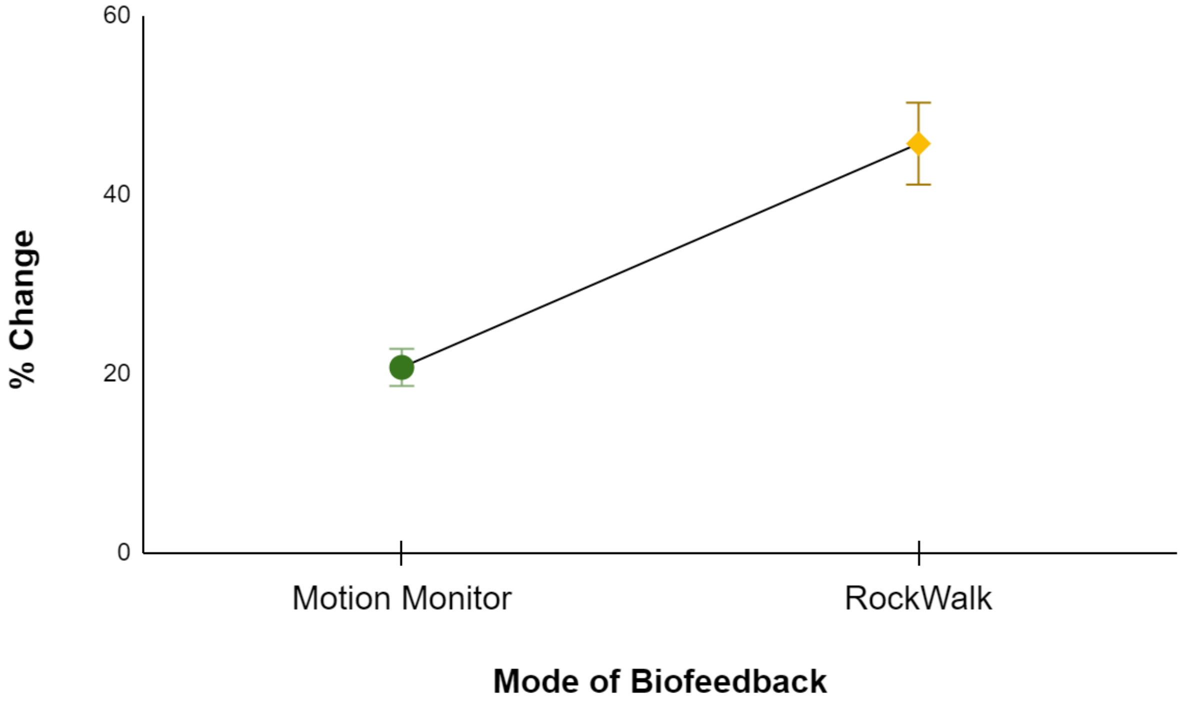
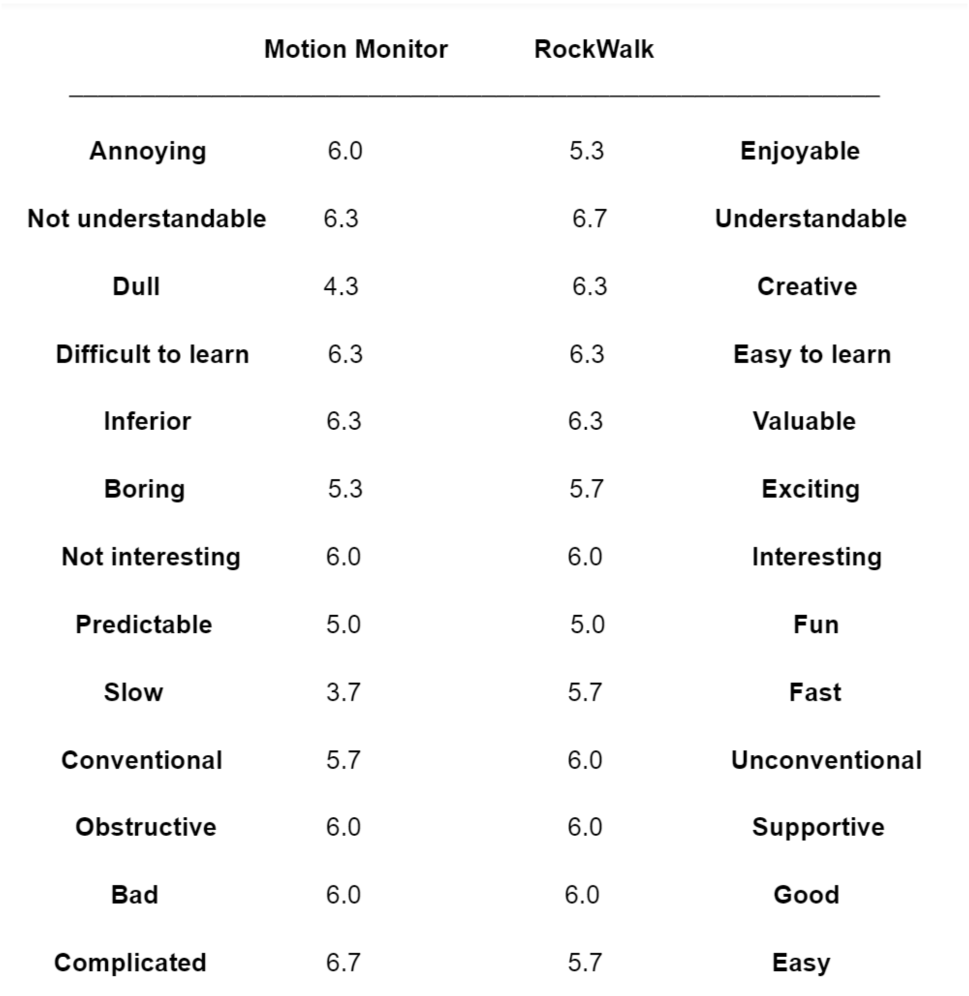


Figure 16. Percent change of average RPE of able-bodied participants exposed to different modes of biofeedback from baseline.

Engagement Questionnaire Scores

RockWalk was found to be more fast-paced (5.7 vs 3.7) and creative (6.3 vs 4.3) compared to Motion Monitor. However, the rest of the questionnaire scores were found to be comparable between RockWalk and Motion Monitor (Table 1).



	Motion Monitor	RockWalk	
Annoying	6.0	5.3	**Enjoyable**
Not understandable	6.3	6.7	**Understandable**
Dull	4.3	6.3	**Creative**
Difficult to learn	6.3	6.3	**Easy to learn**
Inferior	6.3	6.3	**Valuable**
Boring	5.3	5.7	**Exciting**
Not interesting	6.0	6.0	**Interesting**
Predictable	5.0	5.0	**Fun**
Slow	3.7	5.7	**Fast**
Conventional	5.7	6.0	**Unconventional**
Obstructive	6.0	6.0	**Supportive**
Bad	6.0	6.0	**Good**
Complicated	6.7	5.7	**Easy**

***Table 1*. *Average Participant Engagement Scores for Basic Interface Biofeedback (Motion Monitor) and Video Game Biofeedback (RockWalk)*.** *A score closer to 1 represents the "negative" adjective and a score closer to 7 represents the "positive" adjective.*

Discussion

Our preliminary results demonstrated that RockWalk induced increases in skin conductance response, heart rate, RPE compared to baseline. While RockWalk was the most physiological intense mode of biofeedback, the video game was found to be just as engaging and enjoyable as the conventional propulsion biofeedback of Motion Monitor. However, RockWalk was found to be more fast-paced and more creative than Motion Monitor.

RockWalk significantly increased average heart rate compared to baseline. The increased heart indicates greater exertion and effort into producing greater generated propulsive forces, which could explain the significantly greater magnitude of peak AGRF generated (Results from Chapter 1) after exposure to RockWalk. Additionally, RockWalk induced a significantly greater RPE compared to baseline. These results demonstrate that participants subjectively felt that they had greater exertion levels when exposed to video game biofeedback. Meanwhile, Motion Monitor also induced greater heart rate and RPE, though the results were not significantly greater than baseline. Motion Monitor and RockWalk were not significantly different from each other as well. Thus, these indicators may possibly indicate that RockWalk was found to be more intense and difficult compared to baseline than Motion Monitor relative to baseline. However, as the order of biofeedback was not randomized, one may skeptically question the effect of order of biofeedback on these physiological responses. Participants were given a rest in between trials, where they were given time to fill out the engagement questionnaire and receive verbal and video instructions on the subsequent mode of biofeedback, minimizing fatigue bias.

Along with heart rate and RPE, skin conductance response was found to be meaningfully increased in response to video game biofeedback. While not statistically significant, the strong effect size demonstrates the effect of biofeedback on increasing skin conductance response. Higher SCR has been associated with higher affective state, attention, and effort [7,24,46] . Thus, video game biofeedback and its use of a gamified environment and game interface may stimulate a greater sympathetic nervous system response, which could be associated with increased heart rate seen after exposure to RockWalk and could induce greater effort from the participant. Additionally, Motion Monitor was found to have SCR mean amplitude similar to baseline. Possibly, the basic interface did not effectively stimulate the participant's sympathetic nervous system and the boring interface may not have presented an interesting enough stimulus to produce stronger SCRs. Furthermore, Motion Monitor may not have been as challenging in terms of effort and intensity as RockWalk.

Surprisingly, RockWalk and Motion Monitor were found to be similarly fun and engaging. The able-bodied demographic in the study consisted of young adults, and thus the results were interesting that a gamified interface was not subjectively interpreted to be more enjoyable than a simple interface. However, RockWalk was found to be more fast-paced and creative than Motion Monitor. Participants may have been trying to score as many points as they could within their brief trial run and therefore might have found the game to be much faster. If so, video game biofeedback may have the ability to establish faster-pace sessions, thus increasing repetition count and contributing to the effectiveness of a gait training session. Additionally, RockWalk could have been found to be more creative due to the animated environment and use of a badger as the game's avatar, and the creative stimuli could have played a role in producing greater SCR.

Future studies should explore the subjective thoughts of post-stroke individuals on video game biofeedback. As this population consists of elderly adults, it’s quite possible that the consensus is that they prefer a simpler interface, especially since our preliminary results showed that young adults were not particularly or specifically attracted to RockWalk over Motion Monitor.

All in all, video game biofeedback has the potential to increase exertion and effort, maximizing gait training sessions. Further studies are warranted into exploring the engagement potential of video game biofeedback with a greater sample size and with post-stroke individuals.

4. CASE STUDY: FEASIBILITY AND EFFECTS OF GAME-BASED BIOFEEDBACK IN A POST-STROKE PARTICIPANT

Introduction

This section will investigate the results of data collected from one post-stroke participant (69 y) recruited for this thesis. The methods for data collection for the post-stroke participant are available in and consistent with those described in Chapter 1, Chapter 2.3, and Chapter 3.

Results

Magnitude of paretic and non-paretic peak AGRF

Non-paretic AGRF magnitude was much higher than paretic AGRF magnitude at baseline. However, after exposure to Motion Monitor and RockWalk, paretic AGRF magnitude substantially increased, with concomitant slight increases in non-paretic AGRF. RockWalk induced the largest improvements in inter-limb asymmetry between non-paretic and paretic AGRF magnitudes (Figure 17), showing the potential of video game biofeedback in preferentially increasing paretic AGRF while concomitantly minimizing non-paretic AGRF magnitude increases.

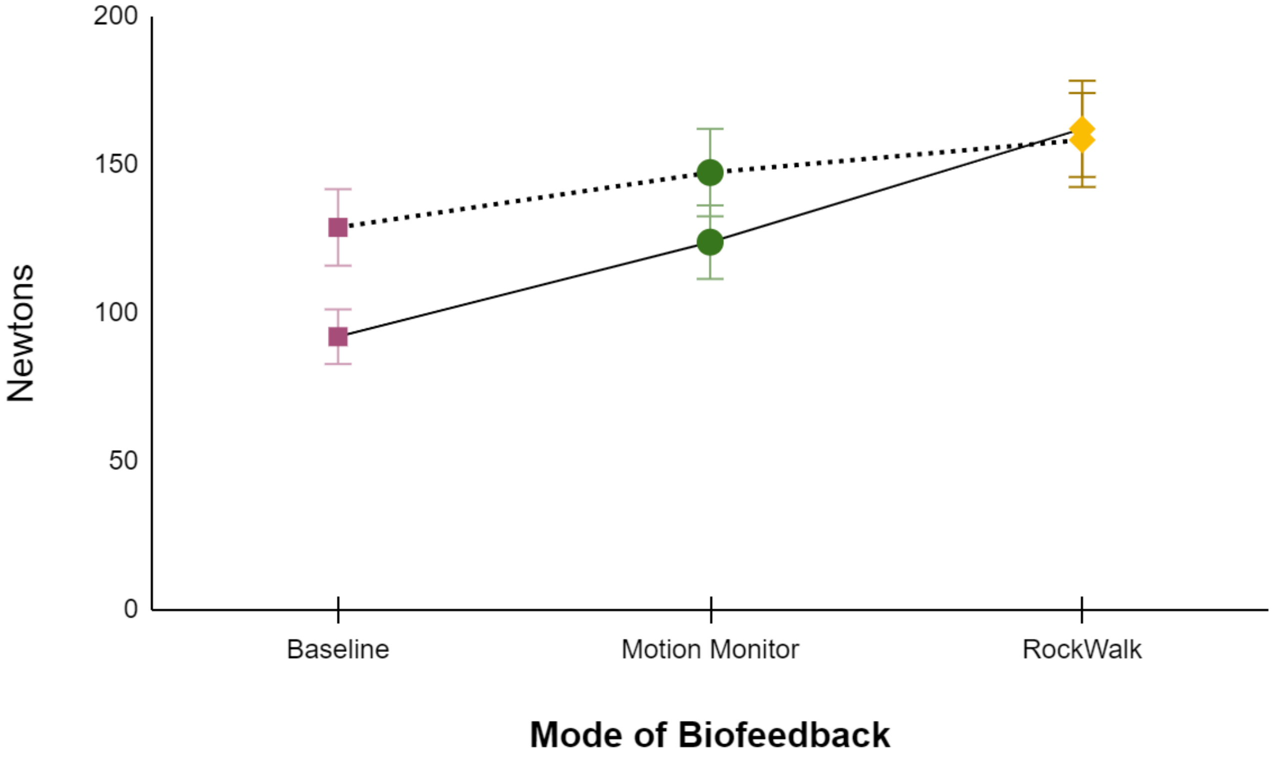


Figure 17. Peak AGRF for the paretic leg (solid line) and the non-paretic leg (dashed line) for different modes of biofeedback

CoV of paretic AGRF magnitude

Similar to able-bodied data, stride-to-stride variability of peak AGRF magnitude increased after exposure to propulsion biofeedback with Motion Monitor, with RockWalk inducing the largest variability.

Timing of paretic peak AGRF

The post stroke participant's timing of peak AGRF was 12% latency for all conditions and demonstrated consistent stride-to-stride timing of peak AGRF for all conditions. This particular participant was high-functioning and had partaken in previous gait training studies in the motion analysis lab, which may have played a role in the relatively normal timing of paretic AGRF similar to the timing of peak AGRF observed in able-bodied individuals.

Physiological Response to Biofeedback

Motion Monitor induced an 8% increase in heart rate (bpm) while RockWalk induced an 18% increase in heart rate. Additionally, Motion Monitor induced 0% increase in RPE while RockWalk induced a 45% increase in RPE. Thus, RockWalk was reported to be much more challenging and difficult than Motion Monitor, and had an even more profound effect on exertion and exercise intensity in this post-stroke individual in comparison to the able-bodied participants.

Interestingly, Motion Monitor gait trial demonstrated higher SCR mean amplitude than RockWalk. Potentially, the post-stroke participant may not have been particularly attracted to the animated game interface and graphics and these gaming features may have instead distracted the individual, contributing to the generation of weaker or smaller magnitude of SCR responses. Therefore, the basic interface of Motion Monitor may have induced higher focus and attention from the individual. Quite possibly, a simpler interface may induce higher focus and attention in an older population and stroke survivors. However, while these results show the feasibility in one stroke survivor, a larger sample study is needed to establish group effects.

Engagement Questionnaire

Similar to the self-reports collected from the able-bodied participants, the post-stroke participant found RockWalk to be faster-paced (score of 7 vs 4 and more creative (score of 6 vs 3) compared to Motion Monitor. The rest of his questionnaire scores were found to be comparable between RockWalk and Motion Monitor. These results contribute to the possibility that video game biofeedback may establish faster-pace sessions, thus increasing repetition count and contributing to the effectiveness of a gait training session.

Discussion

The results from this post-stroke individual demonstrate the feasibility of utilizing video game biofeedback in gait rehabilitative training and offer valuable albeit preliminary insights into the effect of video game biofeedback on a post-stroke participant. Thus, there is a justification to recruit more post-stroke participants to see the effect of video game biofeedback on a greater post-stroke population sample size.

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6. APPENDIX

Picture representing Rating of Perceived Exertion (RPE) shown to participants.

Rating	Perceived Exertion
6	No exertion
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Table. Stroke participant demographics and clinical characteristics. *The average self-selected treadmill speed for the 9 able-bodied individuals was 0.96 m/s (± .07). TM SS – treadmill self-selected speed. OG SS – overground self-selected speed from 10m Walk Test.*

ID	Sex	Age	Affected Side	Months Post-Stroke	Berg Balance Score	Fugl-Meyer Score	TM SS Speed (m/s)	OG SS Speed (m/s)
ST01	M	71	R	106	50	22	0.35	0.46
ST02	F	67	L	65	48	20	0.60	0.90
ST03	F	74	L	24	54	26	0.45	1.12
ST04	M	53	L	7	46	15	0.25	0.32
ST05	M	58	L	6	56	26	0.90	1.03
ST06	F	58	L	64	34	18	0.35	0.44
ST07	M	75	L	8	43	22	0.40	0.96
ST08	M	49	L	46	42	23	0.49	0.49
ST09	M	59	R	78	45	17	0.30	0.88
ST10	M	54	R	27	56	27	0.70	1.33
ST11	M	59	R	15	56	23	0.55	1.08
ST12	M	36	R	35	56	20	0.45	1.23
ST13	F	65	L	19	52	25	0.75	1.25
Mean		**60.1**		**38.5**	**49.1**	**21.9**	**0.49**	**0.88**
SD		**11.1**		**31.3**	**6.9**	**3.7**	**0.19**	**0.34**