Real-Time Feedback to Improve Posture and Gait in Parkinson's Disease:

A Feasibility Study

by

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ABSTRACT

Although tremor, rigidity, and bradykinesia are cardinal symptoms of Parkinson's disease (PD), impairments of gait and balance significantly affect quality of life, especially as the disease progresses, and do not respond well to anti-parkinsonism medications. Many studies have shown that people with PD can walk better when appropriate cues are presented but, to the best of our knowledge, the effects of real-time feedback of step length and uprightness of posture on gait and posture have not been specifically investigated. If it can be demonstrated that real-time feedback can improve posture and gait, the resultant knowledge could be used to design effective rehabilitation strategies to improve quality of life in this population.

In this feasibility study, we have developed a treadmill-based experimental paradigm to provide feedback of step length and upright posture in real-time. Ten subjects (mean age 65.9 ± 7.6 years) with mild to moderate PD (Hoehn and Yahr stage III or below) were evaluated in their ability to successfully utilize real-time feedback presented during quiet standing and treadmill walking tasks during a single data collection session in their medication-on state. During quiet standing tasks in which back angle feedback was provided, subjects were asked to utilize the feedback to maintain upright posture. During treadmill walking tasks, subjects walked at their self-selected speed for five minutes without feedback, with feedback of back angle, or with feedback of step length. During walking tasks with back angle feedback, subjects were asked to utilize the feedback to maintain upright posture. During walking tasks with step length feedback, subjects were asked to utilize the feedback to walk with increased step length.

i

During quiet standing tasks, measurements of back angle were obtained; during walking tasks, measurements of back angle, step length, and step time were obtained.

Subjects stood and walked with significantly increased upright posture during the tasks with real-time back angle feedback compared to tasks without feedback. Similarly, subjects walked with significantly increased step length during tasks with real-time step length feedback compared to tasks without feedback. These results demonstrate that people with PD can utilize real-time feedback to improve upright posture and gait.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

SIGNIFICANCE OF STUDY

Parkinson's disease (PD) is a neurological disorder resulting from the progressive degeneration of dopamine producing cells in the substantia nigra pars compacta (McNeely, 2012). PD is one of the most prevalent neurological diseases and comes second only to essential tremor in prevalence of movement disorders (Louis, 1996). Estimates vary, but worldwide surveys place the number of persons affected by parkinsonism arising from PD as ranging from 50 to 260 per 100,000 in the general population, depending on country, with approximately 1.6% of people over the age of 60 affected (Barbosa, 2006).

Progression of PD and the continued degeneration of the dopamine cells is characterized by four cardinal symptoms which include tremor, rigidity, postural instability, and bradykinesia (Morris, 1996; Morris, 2001). Even when treated, these symptoms can negatively affect a person's gait and lead to difficulties in motor performance exhibited as a reduction in step or stride length, reduction in gait velocity, and increase in cadence (Blin, 1990); in some cases, shuffling or freezing of gait, associated with loss of stride length paired with increased cadence, can occur during gait initiation, turning, or when moving through a narrow passage (Nieuwboer, 2001). Furthermore, PD is characterized by stooped posture and an inability to maintain equilibrium in response to perturbation. The deficiencies in gait and posture associated with PD can increase the age-related risk of falling and negatively affect quality of life;

postural instability, rigidity, and bradykinesia are among the strongest clinical predictors

of falls and the frequency of falling is associated with postural instability (Rogers, 1996).

Traditionally, the symptoms of PD have been treated with medication such as

levodopa (a dopamine precursor) and physical therapy. Dopaminergic medication is

generally successful in managing the classic symptoms of PD, such as rigidity and

tremor, and helps to preserve mobility for a number of years, but is still only partially

effective at treating gait impairment and postural instability (Rogers, 1996). While

medication has been shown to improve aspects of simple forward walking, such as

velocity and stride length, its effects on more complex gait faced in daily living are more

limited and its effects on postural instability and balance are unclear, as impairments have

been observed regardless of medication status (McNeely, 2012). Additionally, over time,

people with PD often experience fluctuating on/off phases characterized by a

reemergence of Parkinson's symptoms between medication doses as medication becomes

less effective. There is evidence that physical therapy can provide a beneficial

supplement to standard medication (Gage, 2004), though it is unclear if it directly

addresses the underlying pathology of PD (Rubenstein, 2002). These issues have led

researchers to explore additional rehabilitation techniques to supplement traditional

pharmacological and physical therapy treatments in an effort to address the symptoms of

PD and improve quality of life.

EXTERNAL SENSORY CUEING

It has long been reported that despite the effects of PD on motor performance,

under certain conditions of visual and auditory aid, persons with PD are still able to

perform movements with relative normalcy (Glickstein, 1991). This has led to the

supposition that effective rehabilitation techniques would allow persons with PD to bypass deficient motor control mechanisms. To this end, studies investigating the effectiveness of external sensory cueing to mitigate deficits in motor performance have been conducted as far back as 1967 (Rubenstein, 2002).

Morris (1996) theorized that the basal ganglia (BG) are involved in two separate elements of motor control that are negatively affected by the pathophysiology underlying PD. First, that the BG interact with the supplementary motor area (SMA) during the execution of learned movements, such as walking, and supply the SMA with internal phasic cues necessary to effectively string together submovements within a movement sequence. The BG discharges at the end of each submovement and this discharge is thought to trigger each submovement within the sequence; PD disturbs the ability of the BG to interact with the SMA, which in turn disrupts the ability of the SMA to execute movement sequences and produces abnormal movements. Second, that motor set related activity in the BG contributes to set-related activity in the SMA in preparation for whole movement sequences; PD may lead to deficits in the motor set and contributions of the BG to whole movement sequence preparations.

Taken together, the two components of the Morris theory have been used to explain various gait deficiencies observed with the progression of PD. Abnormalities in movement elements such as shuffling or short step lengths are thought to be resultant from the deficiencies in the motor set (Morris, 1996) while a lack of smooth movement execution or abnormally long durations for each submovement has been attributed to improperly supplied internal rhythmic cues (Morris, 1996; Rubenstein, 2002). Sensory cueing has been explored as a means to enhance BG function through supplementing

3

internal rhythmic cues or providing external information to augment the motor set, rerouting attention to tasks away from automatic pathways of the basal ganglia and activating alternate motor pathways (Rubenstein, 2002); these sensory cues are often presented as external auditory or visual signals.

Auditory Cues. Auditory cues are generally presented as rhythmic auditory stimulation (RAS) produced by a metronome or click tone generator; RAS is matched with a baseline cadence and then usually increased in an attempt to attain an optimal walking pace (Spaulding, 2013). While the exact mechanism by which auditory cues improve Parkinson's gait is unknown, it is believed that it may compensate for deficiencies in the internal rhythmic cueing of the BG and provide the necessary triggers to switch between submovements in the movement sequence (McIntosh, 1997; Rubenstein, 2002).

Visual Cues. As with auditory cues, the precise mechanism for improvement of Parkinson's gait with visual cues, often presented as floor markers in the form of evenly spaced transverse tape lines, is unknown. It is believed that visual cues may supplement deficient motor sets by focusing attention on walking tasks and walking with correct stride lengths. This is supported by a comparison of visual and attentional cues by Morris (1996) which found similar improvement and carryover effect between cueing strategies during a walking task, and similar deterioration of the carryover effect when increasingly complex secondary tasks were introduced; these findings seem to indicate that attentional strategies and visual cues utilize similar mechanisms to bypass deficient BG-SMA pathways. Azulay (1999) theorized that the benefits of visual cues were not due solely to attention and studied the effects of stroboscopic lighting on the effectiveness of

transverse tape lines. They found that the stripes induced an increase in velocity and stride length, but that these benefits were lost when stroboscopic lighting was applied, thereby removing the perception that the lines were moving downward in the visual field; these findings seem to indicate that the perception of movement in the visual field also aids in bypassing defective BG pathways.

Effectiveness of Sensory Cueing. Regardless of mechanism, auditory and visual cues have been reported to lead to improvements in gait for persons with PD. In a research review, Rubenstein (2002) reported that several single session studies exploring the effects of RAS had shown improvements to velocity, cadence, and stride length that persisted short term after the stimulation had ended; McIntosh et al (1997) found that providing RAS at +10% of baseline cadence resulted in improvements to cadence, stride length, and velocity even when off medication. Similar improvements to stride length and velocity were reported for studies investigating the use of visual cues, including those of the previously mentioned Morris and Azulay. Other recent reviews of sensory cueing research conducted by Spaulding et al (2013) and Rocha et al (2014) have also reported improvements to step length, stride length, cadence, and velocity during various studies attributed to auditory cues and improvements to step or stride length attributed to visual cues. However, the findings of Morris et al (1994) indicate that visual cueing may be more effective in improving stride length than auditory cueing; it was found that when velocity was held constant, auditory cues resulted in an increase in stride length to approximately 80% of normal, as determined by comparison to age matched controls, whereas visual cues resulted in an a stride length that was not significantly different from normal.

5

DYNAMIC CUEING

Recently, two studies (Frazzitta, 2009; Schlick, 2011) have sought to take traditional visual cueing techniques a step further by exploring the effectiveness of dynamic visual cueing, which utilizes alternating left and right step length cues that can more easily be adjusted than traditional tape lines, in conjunction with body-weight supported treadmill training (BWSTT) and treadmill training without body-weight support (TT). Both BWSTT and TT have previously been shown to be effective in improving gait in PD (Frenkel-Toledo, 2005; Miyai, 2000; Toole, 2005) regardless of the level of body-weight support. Frenkel-Toledo (2005) has also theorized that the treadmill works to improve gait by acting as external rhythmic stimulation to somatosensory pathways.

One case study (Schlick, 2011) used a six session protocol for a single Parkinson's subject wherein dynamic visual cues for step length were presented during BWSTT. These cues were projected directly onto the treadmill belt and alternated for the left and right foot, the subject was asked to hit the center of each cue with the appropriate foot as she walked; the distance along the belt between left and right cues was increased before each training session. When results from the cued condition and a non-cued condition were compared, the increase in step length during the cued condition was found to be significantly larger. Similarly, a forty subject study conducted by Frazzitta (2009) compared visual cueing protocols with and without treadmill walking. One group of twenty participated in a cueing protocol wherein subjects were asked to match a target presented on a monitor in front of the treadmill with alternating images of a left or right footprint by taking an appropriately large stride; the remaining twenty subjects underwent

a traditional visual cueing protocol involving transverse tape lines placed on the floor. When results were compared, it was found that the improvements to gait experienced by the group that participated in treadmill walking with visual cues presented on the monitor was significantly greater than that of the group that had not.

Taken together, these studies present interesting findings on the benefits of combined rehabilitation protocols and show that the combination of techniques such as treadmill training and visual cueing can produce greater improvements to gait than can be derived from either technique on its own. Interestingly, while dynamic visual cueing was utilized in both studies, the primary focus of each was the combined effects of treadmill training and visual cueing, and while the study by Frazzitta et al provided feedback of step length, no comparison was made between the presentation of feedback during treadmill walking and treadmill walking alone; neither study explored the potential benefits derived specifically from providing feedback of gait through the presentation of visual cues to encourage walking with a desired step length.

PURPOSE OF THE STUDY

Although visual cueing techniques have long been utilized to supplement physical therapy treatments for the symptoms of PD, and multiple studies have shown their effectiveness in improving gait, to the best of our knowledge, no study has been performed to specifically investigate the effects of real-time feedback in improving step length. Also, despite the negative effects of stooped posture on step length and recovery from perturbations, to our knowledge, no study has investigated providing feedback of uprightness to improve posture. Therefore, we have developed a treadmill-based

7

experimental paradigm to provide feedback of step length and upright posture through real-time visual cues.

This study aims to investigate the hypotheses that (1) persons with PD are able to utilize real-time feedback of their step length to maintain an increased step length compared to their baseline value and (2) persons with PD are able to utilize real-time feedback of their back angle to maintain upright posture. If it can be demonstrated that real-time feedback can improve posture and gait for persons with PD, this information could be used to design effective rehabilitation strategies to improve quality of life in this population.

CHAPTER 2

METHODS

SUBJECTS

Eleven subjects with mild to moderate PD (Hoehn and Yahr stage III or below, see Appendix A for H&Y scale; Goetz, 2004) completed the study. Ten subjects (mean age 65.9 ± 7.6 years) were included in the analysis; one subject had difficulty walking on the treadmill, which affected the quality of data, and was not included in the analysis. The study was approved by the Institutional Review Board of Arizona State University and all subjects provided their written informed consent and permission for photography and videography (see Appendix C for IRB approval form).

Inclusion criteria for the study were: age between 50-80 years, idiopathic PD according to UK brain bank criteria (see Appendix B; Hughes, 1992), Hoehn & Yahr stage I-III in "medication-on" state, ability and willingness to perform testing that involved standing and treadmill locomotion, and stable dosing of PD medication for two weeks prior to participation in the study. Subjects were scheduled for an experimental session approximately one hour after a dose of PD medication to ensure participation during the "medication-on" state, during which the medication effectively controls PD, and to avoid the recurrence of motor fluctuation resulting from end of dose deterioration.

Subjects were excluded if they exhibited: significant dyskinesia, on/off motor fluctuations, freezing, falls or history of falls that would affect subjects' safety or compliance with the study, recent history of unstable heart disease or lung disease, untreated chemical addiction or abuse, uncontrolled psychiatric illness, major neurological problems other than Parkinson's disease, major musculoskeletal or

metabolic problems, dementia as defined by DSM-IV criteria, or regular practice of any exercise to specifically improve gait or posture control.

EXPERIMENTAL SETUP

The experimental setup consisted of four main components: a motorized treadmill, computer system for data collection, a computer monitor for presentation of visual feedback (see Figure 2.1), and an Optitrack camera setup used in conjunction with a collection of reflective markers placed on the subject.

The treadmill used during the experiment was a Mobility Research GaitKeeper 2000L motorized rehab treadmill (Mobility Research, Tempe AZ). The treadmill allowed for adjustment of belt speed and the incline of the treadmill walking platform. Subjects were allowed to set the belt speed to a self-selected comfortable walking pace; incline of the walking platform was maintained at zero throughout the experimental session. A magnetic switch built into the treadmill was connected to the subject with a length of cord and served as an emergency stop system during treadmill walking and a gait belt was worn at all times. A computer monitor was placed in front of the treadmill at subject eye level in such a way that the participants could easily see the real-time feedback while performing quiet standing and walking tasks.

A computer running NaturalPoint OptiTrack Tracking Tools™ software (NaturalPoint Inc., Corvallis OR) in conjunction with a custom C++ program handled the collection and processing of step length, step time, and back angle data from the three-dimensional information provided by the reflective markers. The tracking tools software interfaced with eight OptiTrack FLEX V100 cameras that were placed to the sides and rear of the treadmill. The semi-circular configuration provided the cameras with an

unobstructed view of the subject and marker setup while on the treadmill and helped to

avoid data loss due to marker occlusion. Each camera operated at a frame rate of 100

frames per second and calculations were performed for each frame.

The reflective markers were placed on each subject in sets of three to allow for

the tracking of body segments during the experimental session. Each set of three markers

was arranged in a unique triangular configuration comprising a single rigid body; the

unique configuration of each triangle allowed the Tracking Tools software to distinguish

between rigid bodies and track the centroid of each independently. Rigid bodies were

placed on the back (center point between the shoulder blades), the waist (center point at

back of hips), and on each ankle. A modified GoPro camera harness was utilized to attach

a rigid plate with markers on the upper back while the waist markers were affixed to a

rigid plate connected to a gait belt. The ankle markers were affixed to ankle braces worn

over the subject's socks. Figure 2.1 shows a typical marker setup worn by a subject.

Figure 2.1. Left shows the marker setup worn by a subject (with sets of three reflective markers forming rigid bodies on the back, waist, and ankles) as well as the position of the monitor for presentation of feedback relative to the treadmill during experimental tasks. Right shows the individual components of the marker setup including a modified GoPro harness with rigid plate for back markers, gait belt with rigid plate for waist markers, and ankle braces for foot markers. Optitrack cameras tracked the rigid bodies' three-dimensional location and allowed for the calculation of step length, step time, and back angle.

VISUAL FEEDBACK DESCRIPTION

Visual feedback of either upright posture or gait was presented to subjects in real-time on the monitor in front of the treadmill utilizing two separate feedback paradigms. Postural uprightness was determined through the measurement of a subject's back angle during experimental tasks. Back angle was defined as the angle formed by the horizontal line and the line joining the rigid body of the back (center point between shoulder blades) and the rigid body of the waist (center point at back of the hips). The angle between the

markers was calculated as the arctangent of the difference in the vertical direction over the difference in the anterior-posterior direction of the rigid body centroids; therefore 90 degrees corresponds upright posture (Figure 2.2).
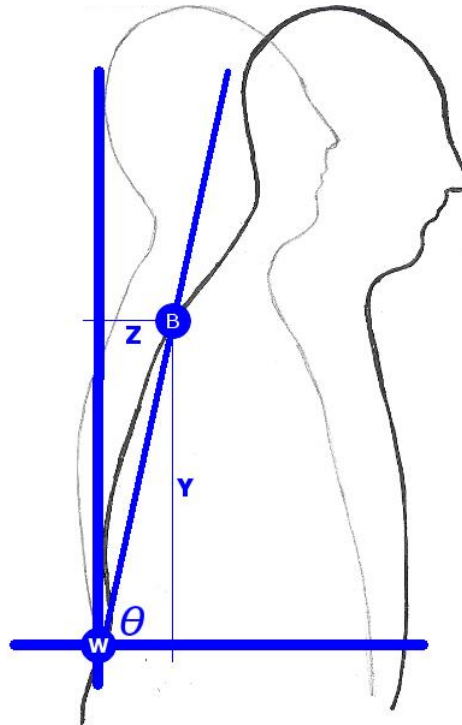

Figure 2.2. The back angle (θ) was calculated as the angle from horizontal of the imaginary line passing through the markers of the back and the markers of the waist. Angle was calculated as the arctangent of $(By - Wy)/(Bz - Wz)$.

The value for maximum uprightness of each subject was measured initially by asking the subject to be as upright as possible. During presentation of feedback, the instantaneous uprightness of the subject was indicated on-screen by a filled green circle (posture cursor), with maximum uprightness represented on the display when the posture cursor overlapped completely with the red circular boundary (standing target) (Figure 2.3). If the subject leaned forward, or stooped, the posture cursor moved up on the screen relative to the standing target; conversely, if the subject leaned backward, the posture cursor moved down on screen relative to the standing target. During walking, the pelvis

13

moves slightly up and down, resulting in similar movement of the reflective markers

placed on the back and center of the pelvis. This would result in slight periodic variations

in the uprightness during walking with corresponding movement of the posture cursor

relative to the target. To account for these periodic movements during walking tasks, the

target zone was increased and subjects were instructed to walk so that the posture cursor

was kept within the inner boundary of the cyan circular region (walking target zone); the

inner and outer radius of the walking target zone were set at 5º and 15º, respectively.
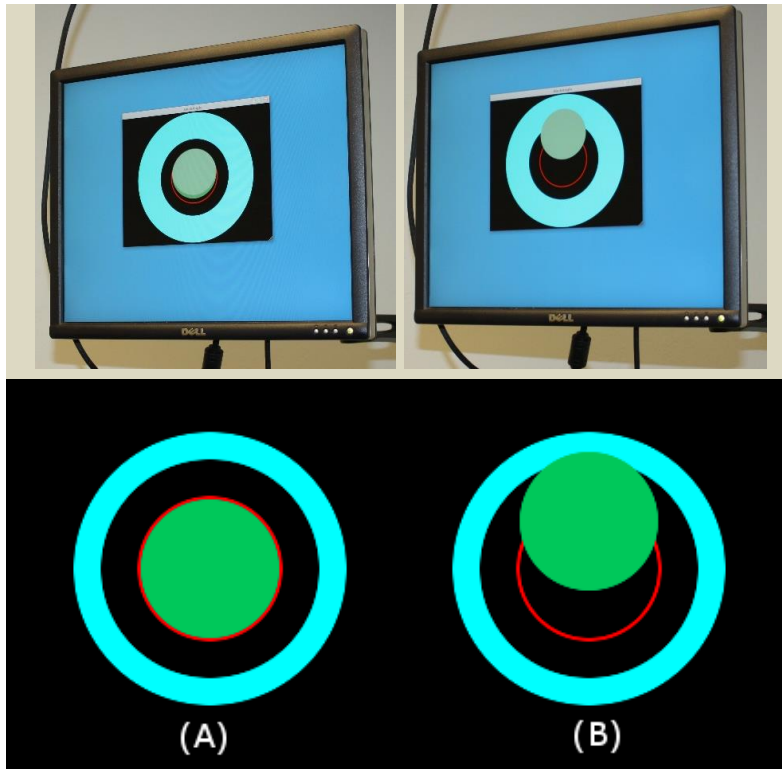

Figure 2.3. Top: shows back angle feedback as seen by the subject; the top left shows feedback when the subject is upright, the top right shows feedback when the subject is bent, or stooped, forward. Bottom: when the subject is upright, the green indicator circle (posture cursor) falls within the red (standing target) or cyan (walking target zone) circles (A); when the subject leans forward (stoops), the posture cursor moves upward on the screen relative to target circles (B). To maintain maximum uprightness, the subjects were asked to keep the posture cursor within the standing target during quiet standing trials and to keep the posture cursor within the inner boundary of the walking target zone during walking trials.

Step length was measured during the experimental session for both left and right feet separately (Figure 2.4). The instantaneous left and right step length was measured as the distance between toe lift and heel strike of the corresponding foot; this definition may differ from step length reported for overgound walking. Toe lift and heel strike positions were determined by tracking the position of the rigid bodies on either ankle and determining minimum and maximum values along the anterior-posterior direction respectively; step length for a given step was calculated as the difference between a sequential minimum and maximum value for each rigid body centroid.
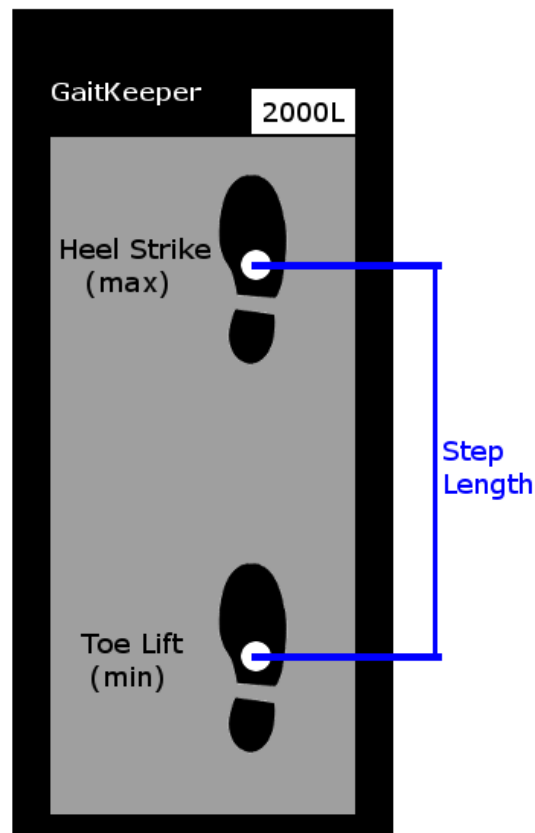

Figure 2.4. The step length was calculated as the difference between toe lift and heel strike positions for each foot which were determined as the respective minimum and maximum foot positions along the anterior-posterior direction.

During presentation of real-time feedback of step length, the instantaneous left and right step length was indicated on the monitor by black left and right foot icons on a white background (Figure 2.5). Blue target lines were displayed on-screen to indicate the desired upper and lower target bounds for step length and set at ±10% of target step length; target step length was determined by increasing the average step length calculated from a non-feedback task by 20%. If a subject's left or right step length was larger or smaller than the target range (area between the two horizontal lines), the display of the corresponding foot icon relative to the target range indicated the amount of deviation. The step length feedback window could be adjusted to display any portion of the step length range between zero and one meter, thereby zooming in on a desired target range.
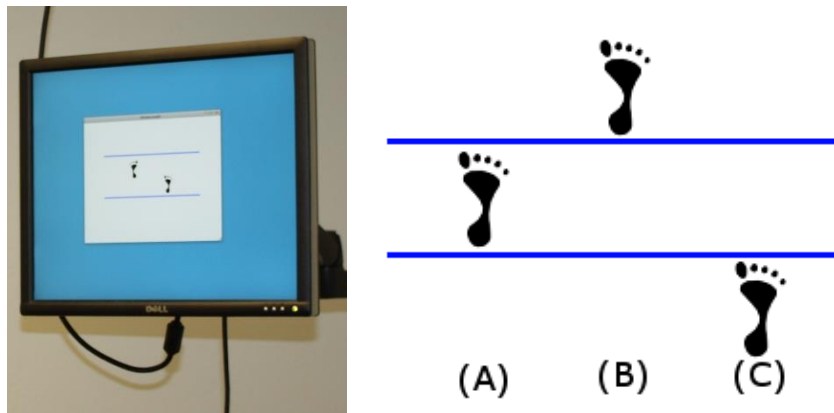

Figure 2.5. Left: shows step length feedback of left and right feet as seen by subjects. Right: subject left and right step length was displayed on screen as left and right black footprints (only right footprint is shown for descriptive purposes). Blue lines indicated the target range, set at ±10% of desired step length; if a subject walked with the desired step length, the footprint would fall between the blue lines (A). If subject's step length was larger or smaller than the target range, the footprint would fall above the top line (B) or below the bottom line (C).

EXPERIMENTAL TASKS

Subjects participated in a single-day data collection session which lasted approximately three hours and consisted of eight experimental tasks with rest periods

16

between each task. Tasks were divided between quiet standing and treadmill walking, half of which included the presentation of real-time visual feedback. Two members of the research team were present during all experimental tasks to ensure subject safety and subjects were allowed to hold the treadmill handles if support was needed. The subjects were also asked to wear a gait belt as part of the marker setup as an additional safety precaution.

Tasks 1, 3, and 4 focused on quiet standing during which subjects were asked to stand at the center of the treadmill belt while the treadmill was off. The subjects were asked to stand on the treadmill, rather than on the ground, in order to facilitate the presentation of feedback as the monitor was placed in front of the treadmill at subjects' eye level. The subject's footprints were marked on a paper aligned with specific points on the treadmill belt to ensure a consistent position and stance throughout all quiet standing tasks.

Task 1 consisted of three quiet standing trials with no feedback, each lasting one minute. Subjects were asked to stand comfortably with hands at their side while facing the monitor in front of the treadmill but were given no additional instructions. In Task 3, subjects were asked to stand with hands at their side while maintaining their maximum uprightness for a single 30-second trial to obtain a measurement of back angle representing subjects' maximum uprightness. In Task 4, subjects were instructed to follow the same procedure for Task 1, but were asked to utilize real-time feedback of back angle to maintain maximum upright posture by overlapping the posture cursor with the standing target.

Tasks 2 and 5 were treadmill walking tasks focused on back angle feedback. Prior to Task 2, subjects were provided an opportunity to adjust to walking on the treadmill and were asked to select a comfortable walking speed that they could maintain for subsequent five minute walking trials. The speed selected during this period was used for Tasks 2 and 5. In Task 2, subjects were asked to walk at their self-selected speed and usual posture for five minutes; no additional instructions or feedback were provided. In Task 5, subjects were asked to walk at their self-selected speed while utilizing real-time feedback of back angle to maintain maximum uprightness by keeping the posture cursor inside the walking target zone.

In Task 6, subjects were again asked to walk at their selected speed without any visual feedback. Eight of the ten subjects chose to increase the speed of the treadmill before starting task 6 after having become accustomed to treadmill walking. Three of these eight subjects were asked to complete two versions of Task 6, one at the speed set in Task 2 (Task 6.1) and one at an increased speed (Task 6.2), to facilitate comparisons between treadmill walking tasks.

Tasks 7 and 8 were treadmill walking tasks focused on step length feedback. The mean step length for each foot from Task 6 (or Task 6.2) was calculated using Matlab™ R2013b (MathWorks Inc., Natick MA). In Task 7, subjects were asked to walk for five minutes at their selected speed from Task 6 while utilizing step length feedback to maintain a target step length; the target step length was determined by increasing the average step length calculated from the previous task (Task 6.1 or Task 6.2) by 20%; several subjects were unable to achieve a 20% increase in step length and the target step length was reduced to a 10-15% increase over the previous task. The upper and lower

values that defined the borders of the target range (indicated by the blue lines) were calculated as ±10% of the target step length value. In Task 8, subjects were again instructed to walk for five minutes at their Task 6 speed without any visual feedback.

Measurements of the subjects' back angle were recorded during each quiet standing task (Task 1, 3, and 4). Measurements of the subjects' right and left step length, right and left step time, and back angle were recorded during each treadmill walking task (Task 2, 5, 6, 7, and 8).

Table 2.1

Experimental Task Summary

Task No.	No. Trials/ Trial Duration	Task Type	Feedback	Task Descriptor	Measurements
1	3 / 1 minute ea.	Quiet Standing	None	No Feedback	Back Angle
2	1 / 5 minutes	Treadmill Walking	None	No Feedback	Step Length, Step Time, Back Angle
3	1 / 30 seconds	Quiet Standing	None	No Feedback	Back Angle
4	3 / 1 minute ea.	Quiet Standing	Back Angle	Feedback	Back Angle
5	1 / 5 minutes	Treadmill Walking	Back Angle	Feedback	Step Length, Step Time, Back Angle
6.1 & 6.2	1 / 5 minutes	Treadmill Walking	None	Feedback Removed	Step Length, Step Time, Back Angle
7	1 / 5 minutes	Treadmill Walking	Step Length	Feedback	Step Length, Step Time, Back Angle
8	1 / 5 minutes	Treadmill Walking	None	Feedback Removed	Step Length, Step Time, Back Angle

Task Descriptor used as reference in results chapter figures.

19

STATISTICAL ANALYSIS

For quiet standing tasks, a Friedman nonparametric test was used to compare results within the three trials of Task 1 and within the three trials of Task 4 to ensure there were no apparent trends in the results due to repetition or learning. A Wilcoxon Signed-Rank test was used to compare the averaged trials of Task 1 with the averaged trials of Task 4. A p-value < 0.05 was considered to be statistically significant

For treadmill walking tasks, between-task comparisons for each measure were carried out to determine the ability of subjects to utilize real-time visual feedback to improve posture and gait. Comparisons were conducted with a Friedman test on the set of subjects' mean measurement values for each task. Post-hoc task-by-task comparisons were conducted with a Wilcoxon Signed-Rank test. A p-value < 0.05 was considered to be statistically significant for the Friedman test and a p-value < 0.017 (after Bonferroni corrections for multiple comparisons; $0.05/3$) was considered significant for each of the post-hoc Wilcoxon tests.

All analyses were carried out using SPSS 22 (IBM Corp., Armonk NY). Descriptive statistics are reported as mean (range).

CHAPTER 3

RESULTS

QUIET STANDING WITH BACK ANGLE FEEDBACK

Figure 3.1 shows representative back angle data from one subject while walking

with back angle feedback. Mean values and standard deviations (SD) were calculated for

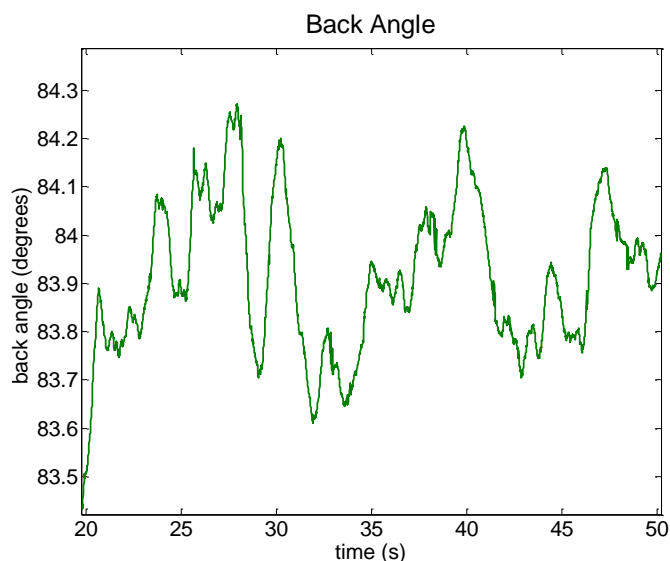the back angle of individual subjects, group data is reported as group mean and range.

Figure 3.1. Representative portion of back angle data from subject during quiet standing
task with back angle feedback.

Figure 3.2 shows comparative mean values and SD of the back angle for all

subjects between quiet standing without feedback and quiet standing with back angle

feedback; as a Friedman test showed no difference between multiple trials of each

condition ($p = 1$ and $p = 0.497$), the average values across trials for each condition were

compared. Across subjects, back angle values were significantly greater for trials with

back angle feedback than without (Wilcoxon test, $p = 0.005$) with group means of 88.7

(13.8) (mean (range)) degrees with feedback versus 86.1 (15.2) degrees for quiet standing

without feedback (where an angle closer to 90 degrees signifies greater uprightness).
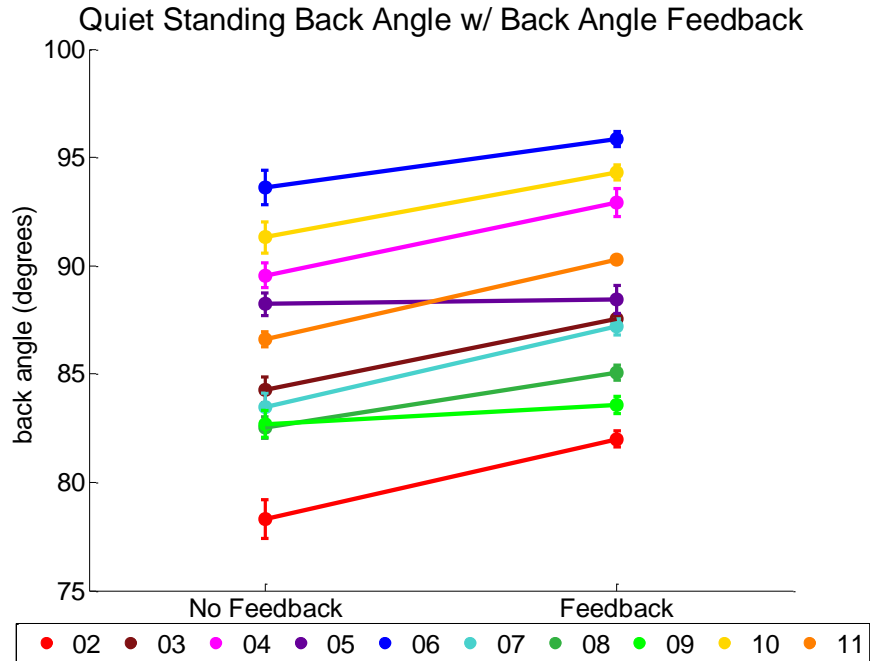
Figure 3.2. Comparison of back angle for quiet standing without feedback (No Feedback) and quiet standing with back angle feedback (Feedback); mean value and standard deviation shown for each subject. There was a significant increase in back angle with presentation of back angle feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.005$).

TREADMILL WALKING WITH BACK ANGLE FEEDBACK

Figure 3.3 shows representative back angle data from one subject during treadmill walking with back angle feedback. Mean values and SD were calculated for the back angle of individual subjects, group data is reported as group mean and range.

Figure 3.4 shows mean values and SD of back angle for all subjects between treadmill walking without feedback and treadmill walking with back angle feedback. Across subjects, back angle values were found to be significantly greater with the presentation of back angle feedback (Wilcoxon test, $p = 0.005$) with group means of 85.3 (18.5) degrees with feedback versus 79.0 (14.4) degrees without feedback (Table 3.1). No significant changes were found for left and right step length or step time between feedback and no feedback conditions. Table 3.1 shows group means for all measures.
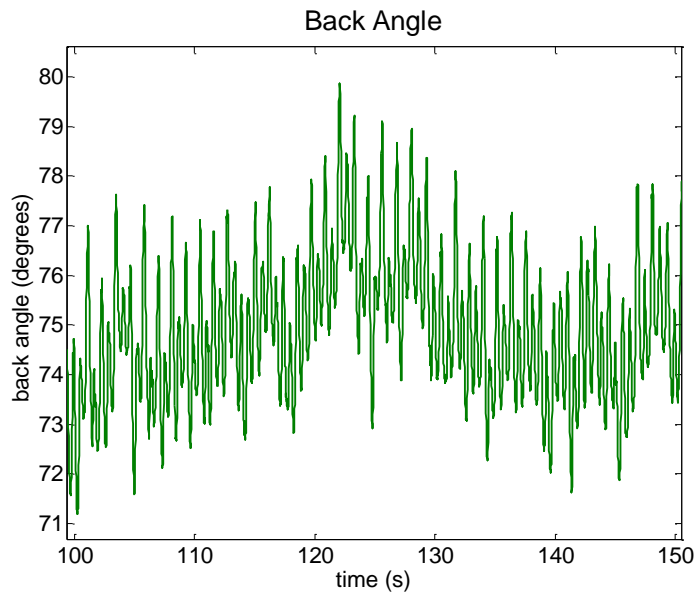
Figure 3.3. Representative portion of back angle data from subject during treadmill walking task with back angle feedback.
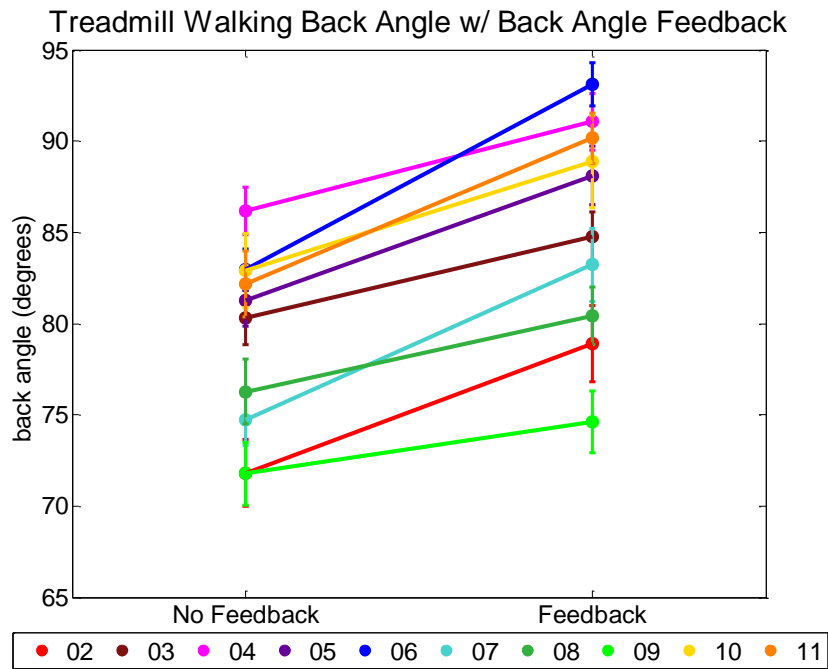

Figure 3.4. Comparison of back angle for treadmill walking without feedback (No Feedback) and treadmill walking with back angle feedback (Feedback); mean value and standard deviation shown for each subject. There was a significant increase in back angle during presentation of back angle feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.005$).

23

Figure 3.5 shows back angle data for each of the treadmill walking tasks: walking without feedback, walking with back angle feedback, and walking after feedback had been removed. Subjects 4, 8, 9, 10, and 11 (shown left) did not increase treadmill speed when back angle feedback was removed; subjects 2, 3, 5, 6, and 7 (shown right) increased treadmill speed when back angle feedback was removed. The top plot in Figure 3.5 shows back angle between each feedback condition while the bottom plot in Figure 3.5 compares walking without back angle feedback and walking after feedback was removed. In addition to a significant increase in back angle between no feedback and feedback conditions, a significant decrease was observed between the feedback and feedback removed conditions (Wilcoxon test; $p = 0.009$); there was no significant difference between no feedback and feedback removed conditions.
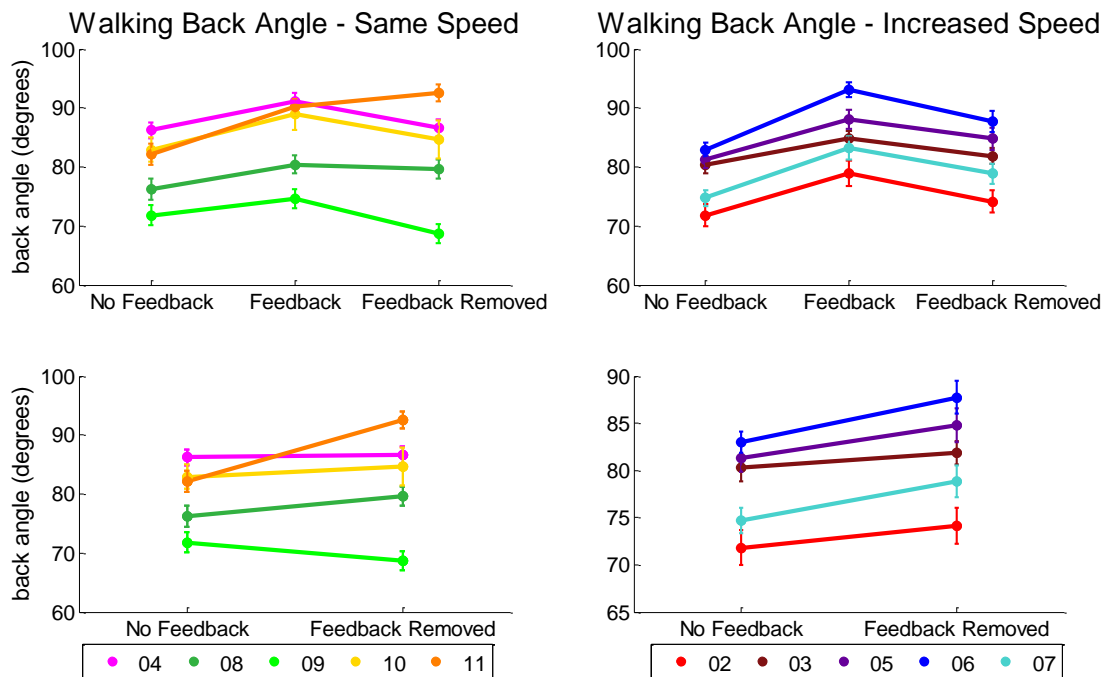

Figure 3.5. Back angle data between treadmill walking tasks without back angle feedback (No Feedback), walking with back angle feedback (Feedback), and walking after feedback was removed (Feedback Removed). Left shows data from Subjects 4, 8, 9, 10, &11 who did not increase treadmill speed when feedback was removed. Right shows data from subjects 2, 3, 5, 6, &7 who increased treadmill speed when feedback was removed.

Table 3.1.

Gait Indices and Back Angle During Treadmill Walking with Back Angle Feedback

Measure	No Feedback	Feedback	Feedback Removed
Left Step Length (m)	0.47 (0.28)	0.46 (0.22)	0.48 (0.22)
Right Step Length (m)	0.47 (0.27)	0.46 (0.17)	0.48 (0.22)
Left Step Time (ms)	509 (193)	503 (160)	497 (130)
Right Step Time (ms)	520 (179)	516 (164)	509 (125)
Back Angle (degrees)	79.0 (14.4)	85.3 (18.5)*	81.9 (23.9)†

Data are mean (range). *significant difference at $p < 0.017$ comparing Feedback to No Feedback. †significant difference at $p < 0.017$ comparing Feedback Removed to Feedback.

TREADMILL WALKING WITH STEP LENGTH FEEDBACK

Figure 3.6 shows representative step length and step time data from one subject during treadmill walking. Mean values and SD were calculated for the left and right step length and left and right step time of individual subjects, group data is reported as group mean and range.
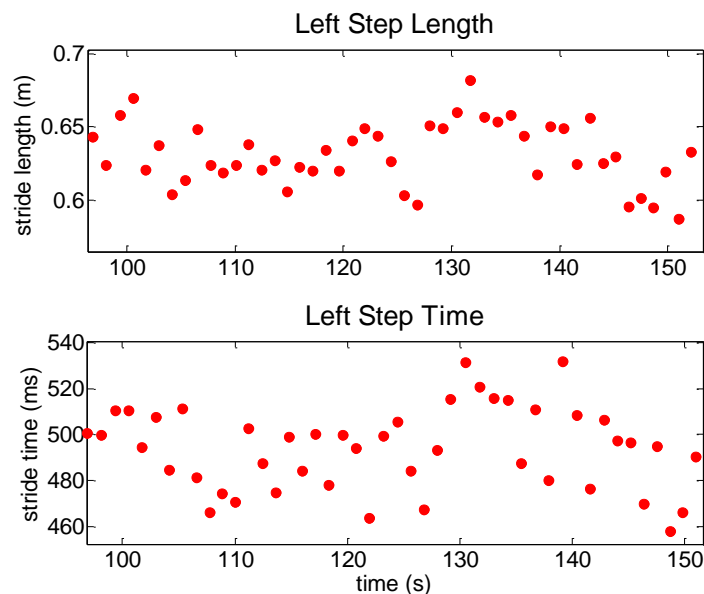

Figure 3.6. Representative portion of step length and step time data for the left foot from a subject during treadmill walking.

Step Length. Figure 3.7 and Figure 3.8 show mean values and SD of left foot and right foot step length respectively between treadmill walking without step length feedback, treadmill walking with step length feedback, and treadmill walking after step length feedback was removed. Across subjects, left foot step length values were found to be significantly higher during the presentation of step length feedback compared to walking without feedback (Friedman test, $p = 0.001$; Wilcoxon test, $p = 0.005$) with group means of 0.56 (0.2) m with feedback and 0.50 (0.25) m without. Right foot step length also increased significantly when walking with step length feedback (Friedman $p = 0$, Wilcoxon $p = 0.005$) with group means of 0.57 (0.17) m with feedback and 0.50 (0.26) m without. No significant changes were found for either right or left step length when feedback was removed as compared to the feedback condition; however, both the right and left step length remained significantly higher when feedback was removed compared to the no feedback condition. Table 3.2 shows group means for all measures.
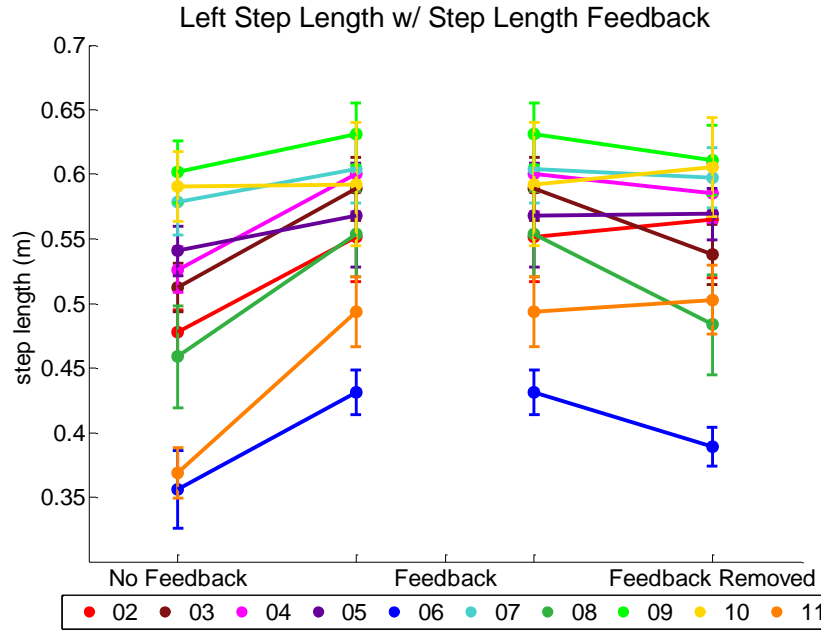
Figure 3.7. Comparison of left foot step length for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). There was a significant increase in left step length during presentation of step length feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.005$). No significant change when feedback was removed.

Figure 3.8. Comparison of right foot step length for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed); There was a significant increase in right step length during presentation of step length feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.005$). No significant change when feedback was removed.
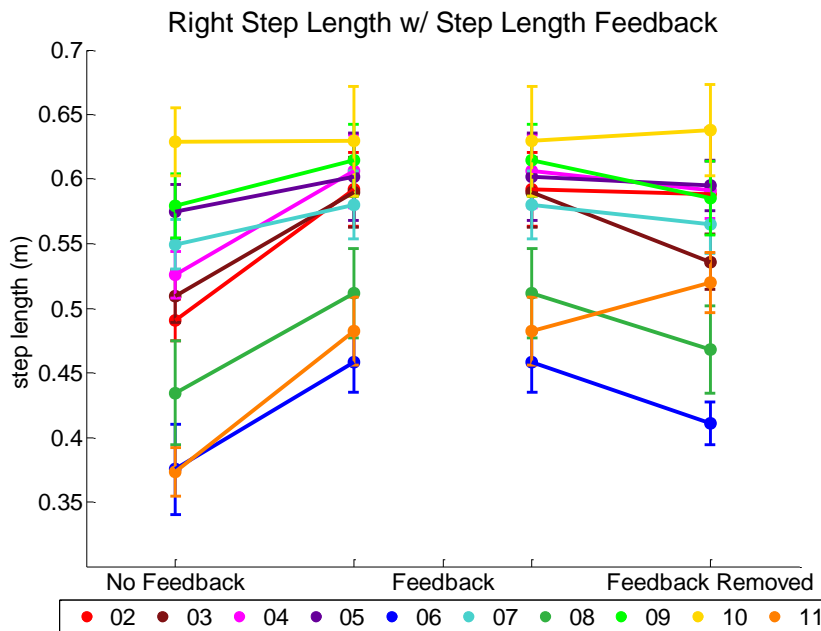
27

Figure 3.9 compares the coefficient of variation for the left and right step length for each step length feedback condition. No significant changes between feedback conditions were detected by a Friedman test or Wilcoxon Signed-Rank test comparison across subjects.

Figure 3.9. Comparison of right and left step length coefficient of variation for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). No significant differences between feedback conditions were found.

Figure 3.10 shows the difference between consecutive right and left step length for each step length feedback condition. Across subjects, no significant changes between feedback conditions were observed with a Friedman test or Wilcoxon Signed-Rank test comparison.

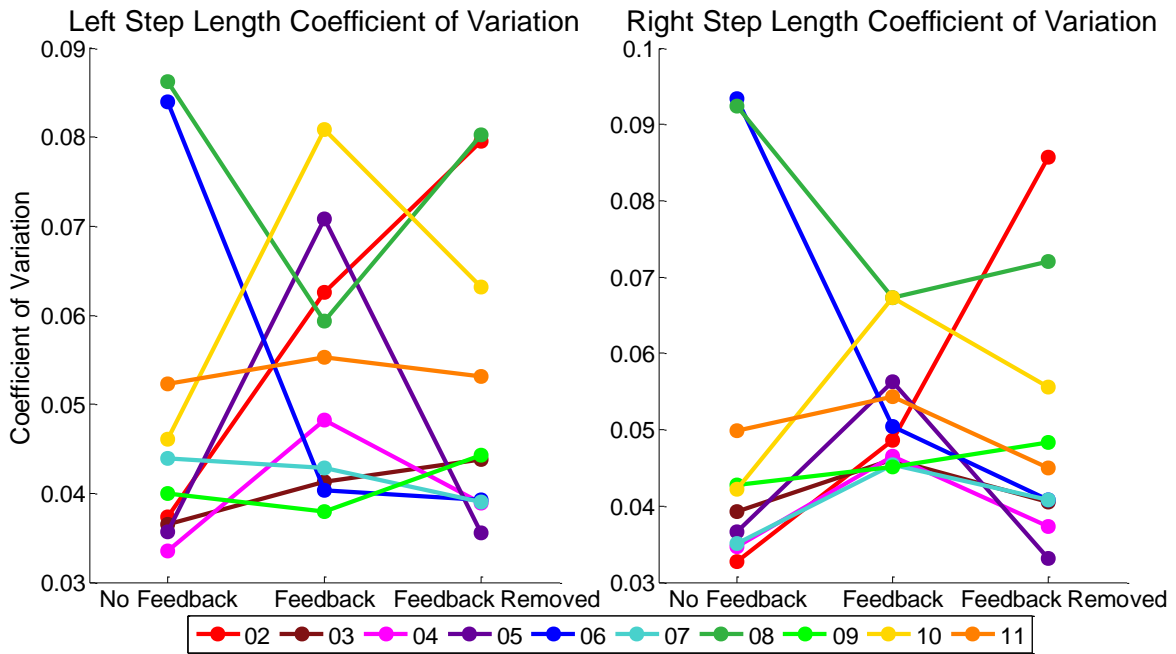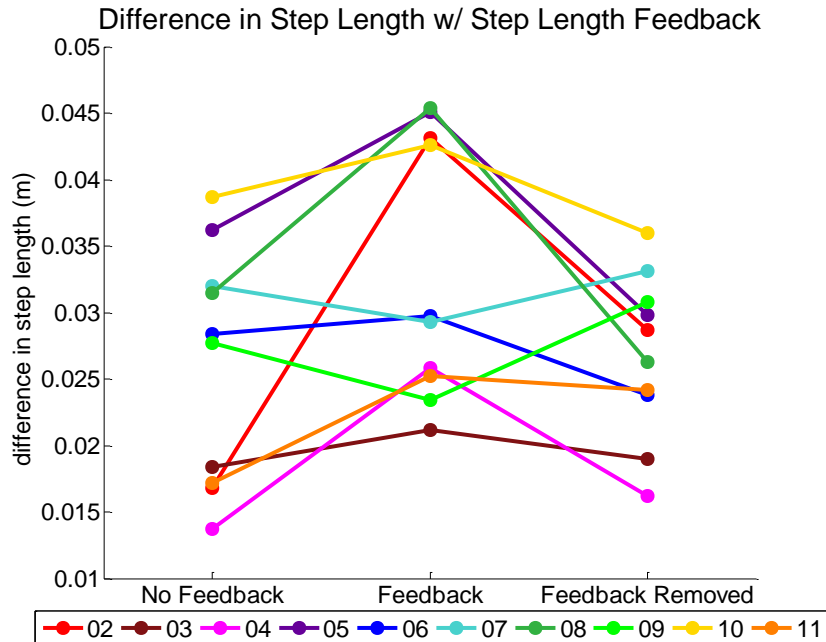*Figure 3.10.* Difference between consecutive right and left step length for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). No significant differences between feedback conditions were found.

Step Time. Figure 3.11 and Figure 3.12 show mean values and SD of left foot and right foot step time respectively between treadmill walking without step length feedback, treadmill walking with step length feedback, and treadmill walking after step length feedback was removed. Left foot step time was found to increase significantly during the presentation of step length feedback (Friedman test, $p = 0.008$; Wilcoxon test, $p = 0.009$) with group means of 495 (130) ms without feedback and 545 (195) ms with step length feedback. Right foot step time increased significantly when step length feedback was presented (Friedman test, $p = 0.025$; Wilcoxon test, $p = 0.017$) with a group mean of 554 (247) ms with feedback and 506 (125) ms without. There were no significant changes between the feedback and feedback removed conditions, but both left and right step times remained significantly higher when feedback was removed compared to the no feedback condition. Table 3.2 shows group means for all measures.

Figure 3.11. Comparison of left foot step time for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). There was a significant increase in left step time during presentation of step length feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.009$). No significant change when was feedback removed.

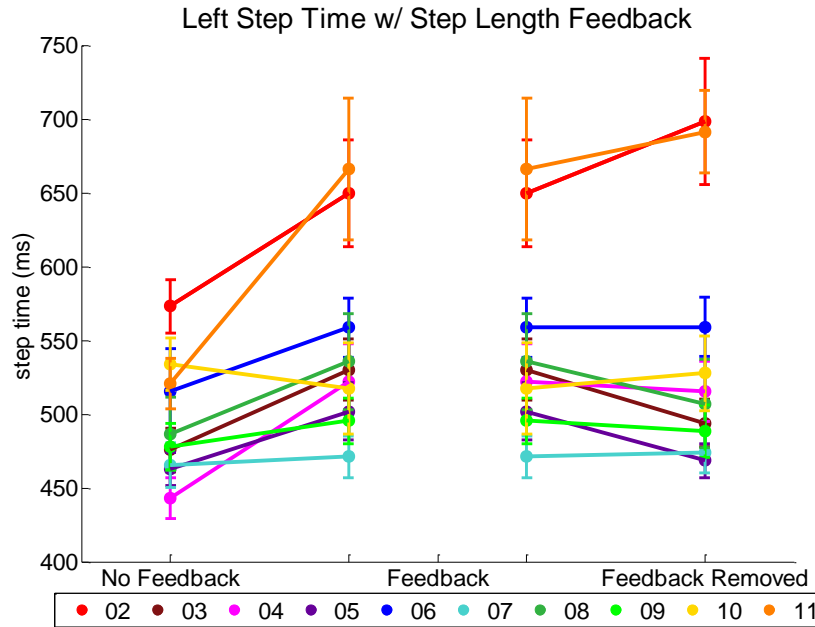*Figure 3.12.* Comparison of right foot step time for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). There was a significant increase in right step time during presentation of step length feedback compared to no feedback across subjects (Wilcoxon test, $p = 0.017$). No significant change when was feedback removed.
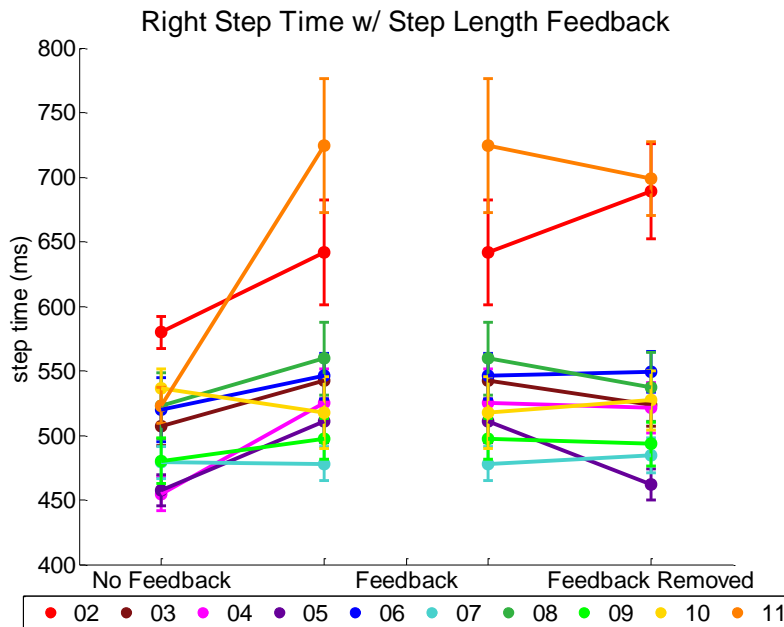
Figure 3.13 compares the coefficient of variation for the left and right step time for each step length feedback condition. A significant change for coefficient of variation of step time was found only for the Friedman test comparison of right foot step time between step length feedback conditions (Friedman test, $p = 0.045$). However, no significance was found when post-hoc task-by-task comparisons were conducted with Wilcoxon Signed-Rank tests. No other significant changes were found for coefficient of variation of step time.

Figure 3.14 shows the difference between consecutive right and left step time for each step length feedback condition. No significant changes between feedback conditions was detected by Friedman or Wilcoxon Signed-Rank test comparisons across subjects.
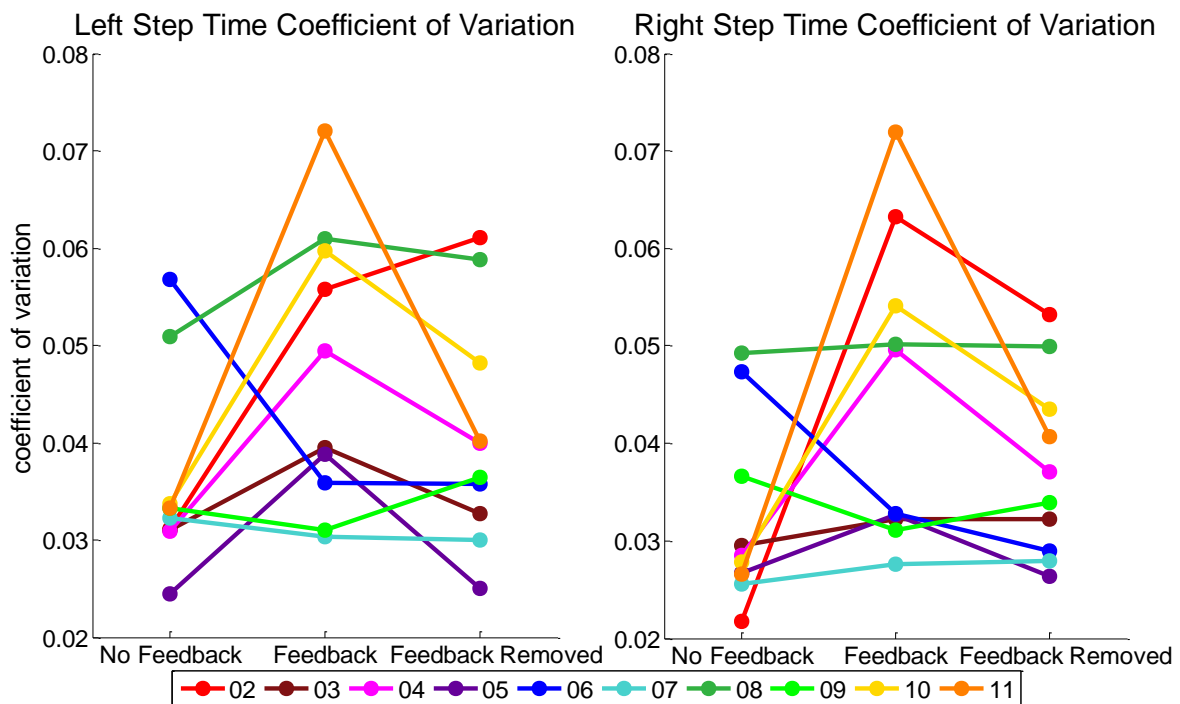

Figure 3.13. Comparison of right and left step time coefficient of variation for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). No significant differences were found with task-by-task Wilcoxon Signed-Rank test comparisons.
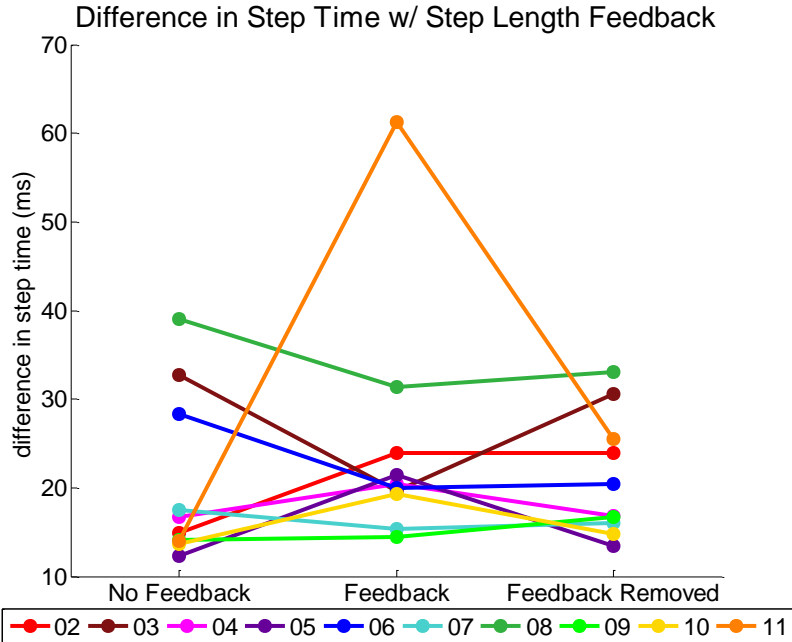
Figure 3.14. Difference between right and left step time for walking without step length feedback (No Feedback), walking with step length feedback (Feedback), and walking with feedback removed (Feedback Removed). No significant differences between feedback conditions were found.

Table 3.2.

Gait Indices and Back Angle During Treadmill Walking with Step Length Feedback

Measure	No Feedback	Feedback	Feedback Removed
Left Step Length (m)	0.50 (0.25)	0.56 (0.2)*	0.54 (0.22)‡
Right Step Length (m)	0.50 (0.26)	0.57 (0.17)*	0.55 (0.23)‡
Left Step Length CoV	0.0496 (0.0527)	0.0539 (0.0429)	0.0517 (0.0447)
Right Step Length CoV	0.0499 (0.0606)	0.0527 (0.0221)	0.0499 (0.0526)
Step Length Difference (m)	0.0261 (0.025)	0.0331 (0.0242)	0.0268 (0.0198)
Left Step Time (ms)	495 (130)	545 (195)*	542 (230)‡
Right Step Time (ms)	506 (125)	554 (247)*	549 (236)‡
Left Step Time CoV	0.0358 (0.0323)	0.0473 (0.0417)	0.0408 (0.0361)
Right Step Time CoV	0.0319 (0.0276)	0.0446 (0.0442)	0.0374 (0.0268)
Step Time Difference (ms)	20 (27)	25 (47)	21 (20)
Back Angle (degrees)	81.3 (24.2)	79.7 (16.6)	81.2 (23.4)

Data are mean (range). *significant difference at $p < 0.017$ comparing Feedback to No Feedback. ‡significant difference at $p < 0.017$ comparing Feedback Removed to No Feedback.

CHAPTER 4

DISCUSSION

Multiple studies have shown the beneficial effects of external sensory cueing on the gait deficiencies caused by PD (Azulay, 1999; Morris, 1996; Rubenstein 2002). Recently, other studies have also explored protocols combining dynamic visual cueing with other forms of PD rehabilitation, such as treadmill training, and found the combination of protocols can produce greater improvement than either protocol on its own (Frazzitta, 2009; Schlick, 2011). To the best of our knowledge, however, no study has been performed to specifically investigate the effects of providing cues in real-time or to investigate the effects of presenting visual cues to improve upright posture.

The purpose of this feasibility study was to begin laying the groundwork for the exploration of the specific effects of the presentation of visual cues in real-time, and the feedback provided by those cues, on improving gait and posture in persons with PD. The two primary hypotheses of this study were (1) that persons with PD are able to utilize real-time feedback of their step length to maintain an increased step length compared to their baseline and (2) that persons with PD are able to utilize real-time feedback of their back angle to maintain upright posture. Therefore, we have developed a treadmill-based experimental paradigm to provide feedback of step length and upright posture through real-time visual cues.

Our results suggest that persons with PD can effectively follow feedback of posture via the presentation of visual cues on back angle. Subjects were able to stand with increased upright posture during the presentation of back angle feedback as evidenced by a significant increase in back angle when subjects were asked to stand quietly with real-

time feedback of back angle compared to standing quietly when feedback of their back angle was not provided. Subjects were also able to walk on the treadmill with significantly increased upright posture when presented with back angle feedback as compared to treadmill walking without feedback.

Results also suggest that persons with PD can effectively follow visual feedback of gait; subjects were able to walk with an increased step length when feedback of step length was provided. This was shown by a significant increase in mean step length of both the left and right foot when real-time feedback of the subject's step length was presented to them on the monitor compared to treadmill walking without presentation of feedback. As subjects were asked to take larger steps without altering the speed during step length feedback trials, an appropriate increase in step time for each foot was also observed between the no feedback and feedback conditions. Interestingly, no significant change was observed for step length or step time of either foot when feedback was removed and subjects once again walked without the presentation of feedback; this may indicate that the benefits of feedback were sustained at least acutely.

There were no significant changes to the coefficient of variation for step length or step time of the left or right foot during the treadmill walking tasks; the difference in consecutive step lengths and step times were also not found to be significantly different between feedback conditions. This seems to reinforce the suggestion that subjects were able to effectively utilize the feedback to increase step length. Generally people with PD walk with increased step length and step time variability and may exhibit asymmetry of gait. Though the step length variability and difference between consecutive steps was not reduced by real-time feedback of step length, they did not worsen significantly while

34

following the feedback. The increase in step length without a corresponding increase in variability or asymmetry indicates that subjects were not only able to take larger steps, they were able to take larger steps without any further deterioration of regularity or rhythmicity.

It should be noted that the Friedman test comparison of treadmill walking with step length feedback showed a significant difference in step time coefficient of variation between feedback conditions; however, task-by-task comparisons (after Bonferroni corrections at $p < 0.017$) with a Wilcoxon Signed-Rank test did not show significant changes. The Friedman test produced a relatively high p-value of 0.045 which might be due in part to the introduction of additional variability to the time data from the software used for data collections. It was noted during analysis that the time between frames of data was more variable than expected. As the time stamp was added to each entry of the data set after the measurements were passed to the feedback software by the camera system, it is unlikely this issue affected step length or back angle measurements, and likely represents a variable delay in post-measurement processing. However, it will need to be addressed and a more reliable means of measuring time determined for future research.

Our results seem to follow, and are likely explained by, the findings of Morris et al (1996), who found that attentional strategies and visual cues had strikingly similar effects on gait patterns in persons with PD. Furthermore, they found that the benefits of both attentional strategies (visualizing and focusing on the walking task and the requisite stride length) and visual cues showed similar levels of deterioration with the introduction of secondary tasks and theorized that both utilized similar mechanisms to bypass

deficient pathways of the basal ganglia by focusing attention on walking. It was also shown that when subjects did not perceive that their walking pattern was being tested, they did not direct full attention to the task and their performance suffered, demonstrating that factors which remind persons with PD to utilize attentional strategies facilitate normal gait. The real-time feedback provided in this study likely operates in a similar manner, requiring them to focus attention on the walking task and providing them with the requisite information regarding their performance to make effective use of attentional strategies. This increased attention to the walking tasks likely helps persons with PD in overcoming some of the proprioceptive sensory deficits associated with PD.

Some studies (Miyai, 2002; Sidaway, 2006) have shown lasting improvements to gait for several weeks following interventions involving visual cueing or treadmill training. It would be beneficial to explore the long term effects of an intervention designed around real-time feedback and determine if similar improvements are possible. Additionally, in the study by Frazzitta et al (2009), subjects were asked to match their stride length to a target stride length by following on screen feedback which alternated between the left and right foot; this feedback paradigm provided information on only one foot at a time rather than both feet simultaneously as in our study. It would be worth investigating the ability of persons with PD to effectively utilize alternative feedback paradigms in improving posture and gait and if the impact of feedback is affected by differences in presentation. Finally, differences in gait between treadmill walking and overground walking have been reported, with walking on a treadmill resulting in slightly shorter stride length (Zijlstra, 1997). If an effective means of measuring step length and back angle and providing real-time feedback without the aid of a camera system or

stationary computer monitor can be developed, it would be worthwhile to compare

relative benefits between feedback during treadmill and overground walking.

This feasibility study has shown that people with PD can utilize the feedback

provided in real-time to modulate and improve their upright posture and step length. The

effectiveness of this type of feedback should be tested in a larger PD population before it

can be utilized in rehabilitation clinics to improve gait and posture in the PD population.

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APPENDIX A

HOEHN & YAHR SCALE

	Hoehn and Yahr Scale
1	Unilateral involvement only usually with minimal or no functional disability
2	Bilateral or midline involvement without impairment of balance
3	Bilateral disease; mild to moderate disability with impaired postural reflexes; physically independent
4	Severely disabling diseases; still able to walk or stand unassisted
5	Confinement to bed or wheelchair unless aided

APPENDIX B

UK BRAINBANK CRITERIA

UK Parkinson's Disease Society Brain Bank clinical diagnostic criteria

Step 1 Diagnosis of Parkinsonian syndrome

- Bradykinesia (slowness of initiation of voluntary movement with progressive reduction in speed and amplitude of repetitive actions)
- And at least one of the following:
    muscular rigidity
    4–6 Hz rest tremor
    postural instability not caused by primary visual, vestibular, cerebellar, or
        proprioceptive dysfunction.

Step 2 Exclusion criteria for Parkinson's disease

- History of repeated strokes with stepwise progression of parkinsonian features
- History of repeated head injury
- History of definite encephalitis
- Oculogyric crises
- Neuroleptic treatment at onset of symptoms
- More than one affected relative
- Sustained remission
- Strictly unilateral features after 3 years
- Supranuclear gaze palsy
- Cerebellar signs
- Early severe autonomic involvement
- Early severe dementia with disturbances of memory, language, and praxis
- Babinski sign
- Presence of cerebral tumour or communicating hydrocephalus on CT scan
- Negative response to large doses of levodopa (if malabsorption excluded)
- MPTP exposure

Step 3 Supportive prospective positive criteria for Parkinson's disease

(Three or more required for diagnosis of definite Parkinson's disease)

- Unilateral onset
- Rest tremor present
- Progressive disorder
- Persistent asymmetry affecting side of onset most
- Excellent response (70–100%) to levodopa
- Severe levodopa-induced chorea
- Levodopa response for 5 years or more
- Clinical course of 10 years or more

APPENDIX C

IRB APPROVAL LETTER

APPROVAL:CONTINUATION

Narayanan Krishnamurthi
CONHI - PhD
602/496-0912
Narayanan.Krishnamurthi@asu.edu

Dear Narayanan Krishnamurthi:

On 1/21/2014 the ASU IRB reviewed the following protocol:

Type of Review:	Continuing Review
Title:	Real-time feedback to improve posture and gait in Parkinson's disease: A feasibility study
Investigator:	Narayanan Krishnamurthi
IRB ID:	1102006053
Category of review:	(6) Voice, video, digital, or image recordings, (3) Noninvasive biological specimens, (7)(b) Social science methods, (7)(a) Behavioral research
Funding:	None
Grant Title:	None
Grant ID:	None
Documents Reviewed:	None

The IRB approved the protocol from 1/21/2014 to 2/21/2015 inclusive. Three weeks before 2/21/2015 you are to submit a completed "FORM: Continuing Review (HRP-212)" and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 2/21/2015 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

Page 1 of 2

IRB Administrator

cc: