Feedback Paradigm for Rehabilitation

of People with Parkinson's Disease

by

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ABSTRACT

Parkinson's disease (PD) is a neurodegenerative disorder that produces a characteristic set of neuromotor deficits that sometimes includes reduced amplitude and velocity of movement. Several studies have shown that people with PD improved their motor performance when presented with external cues. Other work has demonstrated that high velocity and large amplitude exercises can increase the amplitude and velocity of movement in simple carryover tasks in the upper and lower extremities. Although the cause for these effects is not known, improvements due to cueing suggest that part of the neuromotor deficit in PD is in the integration of sensory feedback to produce motor commands. Previous studies have documented some somatosensory deficits, but only limited information is available regarding the nature and magnitude of sensorimotor deficits in the shoulder of people with PD. The goals of this research were to characterize the sensorimotor impairment in the shoulder joint of people with PD and to investigate the use of visual feedback and large amplitude/high velocity exercises to target PD-related motor deficits. Two systems were designed and developed to use visual feedback to assess the ability of participants to accurately adjust limb placement or limb movement velocity and to encourage improvements in performance of these tasks. Each system was tested on participants with PD, age-matched control subjects and young control subjects to characterize and compare limb placement and velocity control capabilities. Results demonstrated that participants with PD were less accurate at placing their limbs than age-matched or young control subjects, but that their performance improved over the course of the test session such that by the end, the participants with PD performed as well as controls. For the limb velocity feedback task, participants with PD and age-matched control subjects were less accurate than young control subjects, but at the end of the session, participants with PD and age-matched control subjects were as accurate as the young control subjects. This study demonstrates that people with PD were able to improve their movement patterns based on visual feedback of performance and suggests that this feedback paradigm may be useful in exercise programs for people with PD.

To my baby manbearpig,

the affectionate nickname my husband gave to our unborn child,

we cannot wait to meet you.

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TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

CHAPTER Page

APPENDIX

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION

Parkinson's disease (PD) is a neurodegenerative movement disorder that results in a characteristic set of neuromotor deficits that sometimes includes reduced amplitude and velocity of movement (Mayeux 2003; Morris 2000). The reduction of movement in people with PD may be a result of their inability to integrate sensory and motor information (Konczak 2007). The goal of this research is to characterize this motor impairment and investigate the use of visual feedback to augment visual cueing techniques and large amplitude/high velocity exercises to reduce the motor deficits of PD.

Studies have shown that people with PD were able to improve their motor performance when presented with external cues. Visual cues such as lines or markers on the floor have been shown to increase stride length and improve stride length regulation during gait (Lim 2005). High velocity and large amplitude exercises have also been shown to increase amplitude and velocity of movement in simple carryover tasks in the upper and lower extremities (Farley 2008; Farley 2005).

Although the exact cause for the marked change using visual cues and intense amplitude of exercises is not known, improvements due to cueing suggest that part of the neuromotor deficit in PD is in the integration of sensory feedback to produce motor commands. Visual feedback may enable users to sense their reduced amplitude of movement and compensate (Abbruzzese 2003).

The sensorimotor loop, with visual cueing and visual feedback, can be represented using the control systems diagram shown in Figure 1. In the diagram, the muscles are used to generate force, the arm/leg represent the systems to be controlled, and the visual and somatic sensory systems provide feedback. The distributed regions of the brain/spinal cord act as the controller, where sensory information is integrated to produce motor commands.

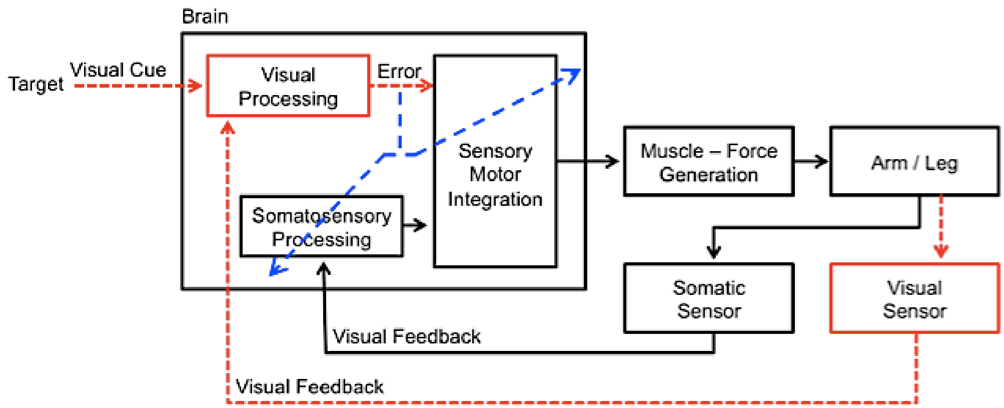


Figure 1. Control System Model of the Sensorimotor Loop With Visual Cueing and Visual Feedback.

1.1. Research Questions

The goal of this research is to characterize the motor impairment of PD and investigate use of visual feedback to augment visual cueing techniques and large amplitude/high velocity exercises to target the reduced amplitude and velocity motor deficits in people with PD.

- **Hypothesis 1a: People with PD have an impaired ability to control active limb placement as compared to that of age-matched control participants.**
- **Hypothesis 1b: Impairment in ability to control active limb placement due to PD is greater than impairment due to aging without PD.**
- **Hypothesis 1c: Visual feedback can be used to improve limb placement in people with PD.**

  Impairment and improvement of limb placement will assessed by measuring the:

  a) accuracy of limb placement at a target location,

  b) repeatability of limb placement at a target location, and

  c) symmetry of movement patterns.
- **Hypothesis 2a: People with PD have an impaired ability to control movement velocity as compared to that of age-matched control participants.**
- **Hypothesis 2b: Impairment in ability to control movement velocity due to PD is greater than impairment due to aging without PD.**

- **Hypothesis 2c: Visual feedback can be used to improve control of movement velocity in people with PD.**

  Impairment and improvement in control of movement velocity will be assessed by measuring the:

  a) ability to produce movements at different speeds,

  b) repeatability of the velocity profile, and

  c) symmetry of movement patterns.

1.2. Specific Aims

- **Aim 1: Design and develop two interactive rehabilitation systems, using visual feedback to encourage: 1) accurate limb placement and 2) movement at different velocities.**
  - **Aim 1-1: Design and Develop Systems**
    - **LPF Mode: Limb Placement Feedback**

      Develop an interactive rehabilitation system to encourage accurate limb placement using visual feedback.
    - **LVF Mode: Limb Velocity Feedback**

      Develop an interactive rehabilitation system to encourage movement at different velocities using visual feedback.
  - **Aim 1-2: Verify System Operation and Suitability of Feedback Tasks**
    - Create preliminary protocol for testing.
    - Perform a preliminary study on participants with PD to: 1) identify any problems with system operation, 2) identify any features or changes to be made to system, 3) refine study protocol for participants with PD, and 4) develop procedures for data analysis.
- **Aim 2: Characterize and compare limb placement and velocity control capability in participants with PD to age-matched and young able-bodied control participants.**

Each feedback system will be tested on participants with PD, age-matched and young able-bodied control participants. Each participant will participate in one session testing each system (limb placement feedback and limb velocity feedback) for a total of two sessions.

Analysis will be performed on this data set to compare the performance of participants with PD to age-matched and able-bodied control participants. We will assess both the pre-intervention capabilities and single-session intervention effects on each group.

- **Aim 2-1: Data Collection**

  Testing will be performed on participants with PD, age-matched and young able-bodied control participants. Each group will be tested on limb placement and limb velocity control. Each session will consist of pre-intervention tests, interventions tasks, and post-intervention tests.

- **Aim 2-2: Data Processing and Hypothesis Testing**

  The movement characteristics, described in Hypothesis 1 and 2, will be extracted from LPF and LVF trials. This data will be analyzed for differences between participants with PD and age-matched and able-bodied control participants (Hypothesis 1a-b and 2a-b) and for changes in movement patterns and velocity control during a single session (Hypothesis 1c and 2c). Assessment will be made based on accuracy, repeatability, smoothness, and other characteristics described in Hypothesis 1 and 2.

1.3. Organization of Dissertation

Chapter 1 introduces the project and presents the specific aims of the dissertation. Chapter 2 presents a review of the literature relevant to this research. Chapters 3 present the design of the Limb Placement Feedback and the Limb Velocity Feedback Systems. Chapter 4 presents the study include and exclusion criteria, the testing procedures, and data analysis procedures. Chapter 5 presents the results Limb Placement Feedback tasks. Chapter 6 presents the results from the Limb Placement Velocity Feedback tasks. Chapter 7 is a discussion of the Limb Placement and Limb Velocity Feedback results and its implication.

CHAPTER 2

LITERATURE REVIEW

The goal of this research is to characterize the sensorimotor deficit of the shoulder and investigate the use of visual feedback to improve limb movement control in people with PD. The rationale for this research is based on the following ideas, which will be discussed in greater detail:

- Parkinson's disease (PD) is neurodegenerative movement disorder that is characterized by hypokinetic movements. (Section 2.1.2 - 2.1.4)
- The sensorimotor deficit of the shoulder has not been well characterized. (Section 2.1.4.1)
- Large amplitude and high velocity exercises have been shown to increase amplitude and velocity in people with PD. (Section 2.2.1)
- Visual cueing, lines or markers on the floor, have been shown to increase stride length, stride length regulation, and velocity in people with PD. (Section 2.2.2)
- The carry-over effects from visual cueing suggest that visual feedback may alter perception of movement derived from somatosensory inputs and/or the process of sensorimotor integration. (Section 2.1.4.1)
- Our interactive rehabilitation systems provide an interactive environment with simple neuromotor tasks that are designed to facilitate investigation of sensorimotor capabilities and delivery of sensorimotor therapy in the shoulder. (Chapter 3)

2.1. Parkinson's Disease

Parkinson's disease is a neurodegenerative disease caused by the degeneration of the dopaminergic nigrostriatal pathway. This degeneration leads to a lack of dopaminergic input to the striatum, which results in the symptoms of Parkinson's disease (Bernheimer 1973).

2.1.1. Epidemiology

Parkinson's disease is the second most common neurodegenerative disease (Dauer 2003), affecting nearly 2% of the population over the age of 65 (Morris 2000) or 1 million people in the United States (Harris 2009; Trail 2008). The average age of onset of PD is in the 60s (Harris 2009; Mayeux 2003) and the risk of PD increases with age (Elbaz 2002; Mayeux 2003).

2.1.2. Basal Ganglia Pathology

Voluntary movement is initiated in the supplementary and pre-motor cortex and is regulated through feedback loops, the direct and indirect pathways, through the basal ganglia and thalamus (Figure 2). The basal ganglia, which is involved in the control of movement, are composed of the striatum (caudate and putamen), globus pallidus interna and externa (GPi and GPe), subthalamic nucleus (STN), and substantia nigra pars compacta (SNpc). The basal ganglia then projects to the thalamus, which provides the integrated sensory and motor information to the cortex.

The direct pathway, which is responsible for facilitating movement, is activated by D1 dopamine receptors that are excited by dopamine (DA). In the direct pathway, neurons project from the putamen to the GPi, to the thalamus, and then to the motor cortex.

The indirect pathway, which is responsible for inhibiting motor movement, is activated by D2 dopamine receptors that are inhibited by DA. In the indirect pathway, neurons project from the putamen to the GPe, to the STN, to the GPi, to the thalamus, and then to the motor cortex. The indirect pathway is so named because it takes an indirect route through the STN to the GPi.

At various steps in the direct and indirect pathways (Figure 3), the excitatory neurotransmitter glutamate or the inhibitory neurotransmitter gamma-amminobutyric acid (GABA) mediate transmission. Glutamate has an excitatory effect on the corticostriatal (putamen), subthalamic-pallido, and thalamocortical pathway. GABA has an inhibitory effect on the striatal projections, pallido-subthalamic, and pallidothalamic pathway. The excitatory pathways are represented by arrows and the inhibitory pathways are represented by terminal lines in Figure 2.

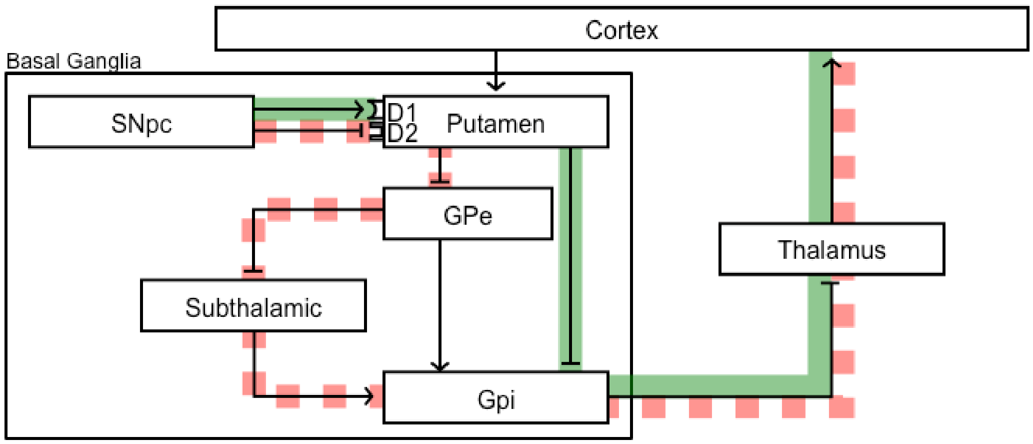


Figure 2. Connectivity in the Basal Ganglia. The arrows represent excitation and the terminal lines represent inhibition of the pathway. The direct pathway is highlighted in solid green; the indirect pathway is highlighted in dashed red.

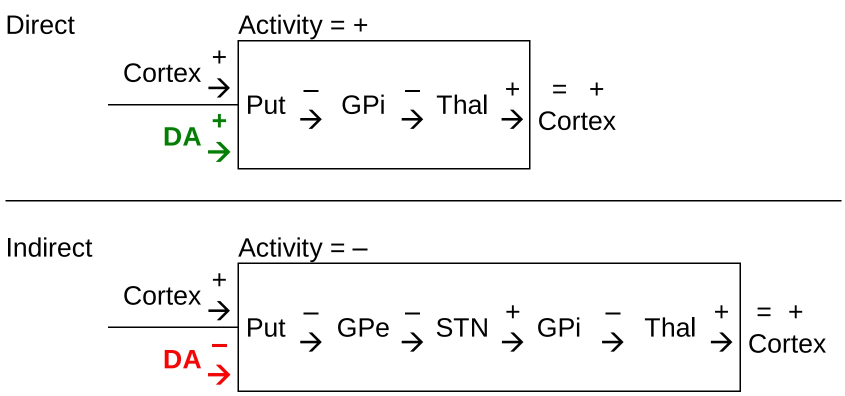


Figure 3. Unimpaired Activation Diagram of the Basal Ganglia. The (+) sign represent excitation and the (–) represent inhibition of the neural pathway. The direct pathway helps to facilitate movement and is excited by dopaminergic input to the putaman via the D1 receptors. The indirect pathway helps to inhibit movement and is inhibited by dopaminergic input to the putamen via the D2 receptors. In the presence of dopamine, the end activity of both pathways is facilitation of movement.

The symptoms of Parkinson's disease are caused by the degeneration of the dopaminergic nigrostriatal pathway or the DA neurons projecting from the substantia nigra pars compacta (SNpc) to the striatum (Mayeux 2003). The degeneration of the nigrostriatal pathway results in reduced dopaminergic input to the striatum with a more significant loss in the putamen than the caudate, although both areas are affected (Dauer 2003).

This impaired release of DA to the striatum results in a reduced excitation of the direct pathway and a reduced inhibition of the indirect pathway (Figure 4). As a result, the indirect pathway is over-expressed and the direct pathway is under-expressed, resulting in a general reduction of movement. Symptoms of PD begin to appear after 70-80% of DA neurons have died (Bernheimer 1973).

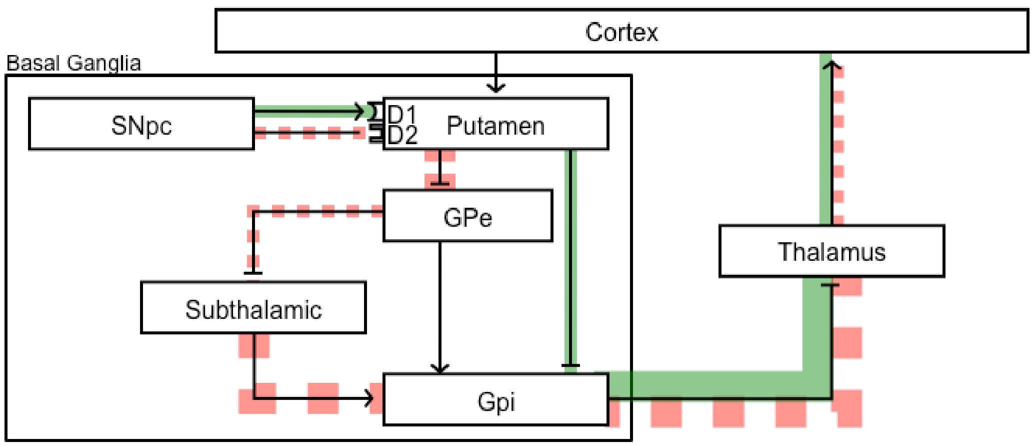


Figure 4. Abnormal Activity in the Basal Ganglia Circuitry Due to PD. The direct pathway is highlighted in solid green; the indirect pathway is highlighted in dashed red.

2.1.3. Etiology

Several gene mutations have been identified as the most common cause of familial Parkinson's disease (Lim 2002); many of these genes are associated with various types of PD, such as: early onset (PARK 1, 2, 3, 6, and 7), rapid progression (PARK 1), presence of Lewy Bodies (PARK 1 and 4).

Although there are familial cases of PD, in most cases the cause of PD is unknown. Many cellular mechanisms for idiopathic have been proposed, including: premature apoptosis, oxidative stress, loss of neurotrophic factors, mitochondrial dysfunction, and neuromelanin degeneration.

Parkinsonism refers to any movement disorder with symptoms similar to Parkinson's disease, including Parkinson's disease. Parkinson's disease, which is sometimes called Primary Parkinsonism, makes up approximately 80% of Parkinsonism disorders. Other non-PD

Parkinsonism disorders include: secondary Parkinsonism, parkinsonism-plus syndromes, and familial neurodegenerative disease. These Parkinsonism disorders generally have known etiologies. Secondary parkinsonism can be induced by drugs, tumor, trauma, toxins (Mn, CO, MPTP, cyanide), hydrocephalus, hypoxia, and other causes (Dauer 2003; Trail 2008). Just as in PD, the symptoms in secondary Parkinsonism are due to decreased DA or damage to the striatal pathways.

2.1.4. Symptoms

The cardinal symptoms of PD are bradykinesia (reduced speed and amplitude), akinesia (difficulty initiating movement), cogwheel rigidity, stooped posture and resting tremor (Mayeux 2003; Morris 2000). Cogwheel rigidity is the resistance to passive movement of the limb. Stooped posture is the forward inclination of the upper torso, which can lead to postural instability and an increased risk of falling.

The first sign of PD is often a unilateral reduction in arm swing during gait or resting tremor in single limb (Mayeux 2003). As the disease progresses, the symptoms become bilateral, more severe, and affect more systems. Hoehn and Yahr divided the progression of PD into 5 stages (Goetz 2004; Morris 2000).

The Hoehn and Yahr (HY) scale, Table 1, was designed to classify the level of disability and track its progression; it is not presumed that every PD subject will progress in order from Stage 1 to 5 (Goetz 2004). Although this staging scale is widely used, its utility is questioned because it is considered by some to be too broad and most people with PD progress in a non-linear fashion between the stages. Another widely used clinical scale is the UPDRS; where activities are individually rated on a scale 1-5, and then totaled to give an overall combined UPDRS score.

Table 1. Hoehn and Yahr Stages

1	Unilateral involvement only, usually with minimal or no functional impairment
2	Bilateral or midline involvement, without impairment of balance
3	First sign of impaired righting reflexes. This is evident by unsteadiness as the patient turns or is demonstrated when he or she is pushed from standing equilibrium with the feet together and eyes closed. Functionally, the patient is somewhat restricted in his or her activities but may have some work potential, depending on the type of employment. Patients are physically capable of leading independent lives, and their disability is mild to moderate.
4	Fully developed, severely disabling disease; the patient is still able to walk and stand unassisted but is markedly incapacitated
5	Confinement to bed or wheelchair, unless aided

The progression of the cardinal symptoms can severely affect the activities of daily living, especially during the later stages of the disease. People with PD show an increase in gait disturbances, including: reduced speed, reduced stride length, reduced stride length regulation, and increased cadence (Morris 1994). During the later stages, shuffling gait, festination, freezing and falls are common. Also common during the early stages of PD are micrographia and monotone voice. Micrographia is characterized by reduced handwriting size, clarity, speed, and increased hesitation during writing (Contreras-Vidal 1995). The reduced speech volume and expression that is often observed in people with PD can lead to monotony. During the later stages, non-movement symptoms, such as dementia, depression, respiratory problems, sleep disturbance, sexual dysfunction, and personality changes may appear (Mayeux 2003). Dyskinesia (involuntary movement) is also frequent during the later stages of the disease due to side effects of the pharmacological treatment.

For a PD diagnosis, at least two of the primary features must be present: resting tremor, bradykinesia, cogwheel rigidity, and postural reflex impairment. Of these primary features one must be resting tremor and/or bradykinesia. The absence of resting tremor and bradykinesia reduce the certainty of the PD diagnosis. Other causes of Parkinsonism, such as dementia, should not be present (Mayeux 2003).

In this work we plan to characterize the reduced amplitude and velocity of movement (or bradykinesia) in the shoulder when compared to age-matched and young able-bodied controls.

As well as to identify if the intervention proposed in Aim 1 will help to improve limb placement and limb velocity control.

2.1.4.1. Sensorimotor Deficits. It has been suggested that the cause of the hypokinetic movement in people with PD may be a result of an impaired somatosensation. Studies of the basal ganglia of non-human primate model of PD (treated with 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine, or MPTP), have shown that most neurons exhibited decreased specificity, with most responding to movements of several joints (Pessiglione 2005). This is in contrast with the undamaged system in which most neurons respond to movements a single joint (Pessiglione 2005). This lack of specificity could lead to impaired perception (Konczak 2007).

Sensorimotor deficits have been shown in the finger, wrist, elbow, and shoulder, with most studies focusing on investigations of elbow and very little on the finger, wrist or shoulder. Studies have shown that people with PD have a greater difficulty than age-matched controls in identifying small externally imposed movement in the finger (Schneider 1987), wrist (Schneider 1987), elbow (Koczak 2007; Zia 2000), and shoulder (Schneider 1987). With respect to the elbow, participants with PD have a greater difficulty in identifying which elbow is more flexed or extended (O'Suilleabhain 2001; Zia 2000), and performing contralateral elbow angle matching (O'Suilleabhain 2001).

Additional studies have shown that people with PD have trouble with multiple joint movements. Studies, Adamovich (2001), Jobst (1997) and Klockgether (1994), have shown that people with PD have difficulty pointing to external targets when vision was occluded. These deficits were exhibited in forward pointing (Adamovich 2001) and table-top pointing (Jobst 1997; Klockgether 1994). People with PD did not have the same difficulty pointed with vision (Adamovich 2001; Klockgether 1994) or when the target was intrinsic, such as when the target was located on the surface of the body/hand (Jobst 1997).

Our research will focus on sensorimotor deficits in shoulder. In particular we will target limb placement in the coronal plane and limb (arm-swinging) velocity in the parasaggital plane. Participants will be given different types of feedback to encourage accurate limb placement and velocity.

2.1.5. Pharmacological and Surgical Treatments

2.1.5.1. Levodopa. There is no cure for Parkinson's disease, so current treatment focuses on reducing the symptoms of PD and increasing life expectancy after onset. The current standard and most effective method of pharmacological treatment for Parkinson's disease is L-3,4-dihydroxyphenylalanine (levodopa or L-dopa) Therapy. L-dopa is the natural metabolic precursor to dopamine that can be taken orally and can freely pass through the blood-brain barrier (Cenci 2007; Miyazaki 2008). L-dopa treats only the symptoms of PD and does not halt the degeneration of the nigrostriatal DA neurons.

L-dopa can improve motor symptoms and lengthen life expectancy after the onset of Parkinson's, but these symptomatic benefits are not permanent. Generally, within 5 years the effectiveness of L-dopa begins to wear-off, produce and on-off fluctuations, and/or dyskinesia (involuntary movement) (Asanuma 2003; Moore 2008). The exact cause of dyskinesia is still largely unknown.

To prolong the effects of L-dopa and reduce dyskinesia, L-dopa is commonly administered with dopa decarboxylase inhibitor (DDI), dopamine receptor antagonist, COMT (catechol-O-methyltransferase) inhibitor, MAO (monoamine oxidase) inhibitor, anticholelinergics, and amantadine during the later stages of the disease (Weiner 2001). Decreasing the dosage and increasing the frequency in which the L-dopa is administered has also been shown to reduce the side effects.

2.1.5.2. Surgical Treatments. There are two different types of surgical treatment: ablative surgeries and deep brain stimulation (Starr 1998). Ablative surgery results in a permanent lesion in the brain by burning or freezing the target tissue area (Starr 1998). Thalamotomy, a lesion in the thalamus, is performed to reduce essential tremor (Diederich 1992; Fox 1991). Pallidotomy, a lesion in the globus plallidus, is performed to reduce L-Dopa induced dyskinesia (Baron 1996; Baron 2000). Subthalamotomy, a lesion in the subthalamic nucleus, is performed to reduce tremor, dyskinesia and freezing gait (Diederich 1992).

Deep brain stimulation (DBS) is the surgical implantation of a stimulation device, which sends out an electrical pulse targeting specific areas of the brain (Starr 1998). The stimulator is implanted in the chest; the electrode lead, a thin insulated wire, is then wired under the skin of the head through a small hole in the skull to allow placement of the electrodes into the targeted deep brain structures. Subthalamic DBS is used to treat tremor, rigidity, and dyskinesia and pallidal DBS is used to treat dyskinesia.

There are some risks associated with ablative surgery and deep brain stimulation. Ablative surgery is irreversible. Any negative side effects (motor, speech, or cognition problem) as result of the surgery could be permanent. Deep brain stimulation is preferable to ablative surgery, since it is reversible and adjustable. With both ablative surgery and DBS there is a risk that the treatment may not be effective and, as with any brain surgery, there is a small risk of stroke, hemorrhaging, confusion and death. Ablative surgery and DBS are typically only used during the later stages of the disease when the other options have been exhausted.

2.2. Physical Therapy Techniques

2.2.1. Intense Amplitude Training

Training BIG is a physical therapy technique that utilizes large amplitude exercises to treat the reduced amplitude of movement in people with PD (Farley 2008; Farley 2005). Its concept is based on previous work demonstrating that amplitude-based cuing increases both amplitude and velocity of movement in simple reaching, walking and speaking tasks.

The Training BIG asks participants to focus on the sensory awareness of the movement ‘bigness.’ The ‘bigness’ of the movement is relative to the typical movement patterns of PD. Examples of BIG movements might include, swinging the right arm across the body while fully extending the right leg then switching sides. Another is reaching the right arm up while stretching the right leg back, then swinging the right arm back and the left arm up while stepping back onto the right leg and fully extending the left leg forward; then alternating sides (Farley 2005). The BIG regime is 4 weeks with 4 sessions/week in the presence of a physical therapist. Participants with PD (HY 1, 2, & 3) all showed increases in reaching velocity at arm’s length + 10 cm. Participants with PD at HY Stage 1 or 2 also showed an increase in preferred gait velocity, but participants with PD at HY Stage 3 did not. Across the group of all participants (HY 1, 2, or 3), increases in stride length during gait at preferred speed and at the 'as fast as possible' speed were observed, and improvements were greater at the preferred speed than at the 'as fast as possible' speed. Greater improvements were seen for participants at the early stages of PD (HY 1) than at the later stages (HY 2 or 3).

In BIG training, participants with PD are asked to focus on sensory awareness of movement with no visual or auditory feedback of limb placement (only physical therapist feedback); participants are asked to focus on intrinsic awareness. Our work aims to deliver extrinsic feedback that will enhance participant's awareness of their limb placement and limb velocity and will encourage them to make larger amplitude and larger velocity movements.

2.2.2. Sensory Cueing

Sensory cueing is the use of an external stimulus used either to initiate movement or to facilitate it. There are two main types of sensory cueing used to encourage movement in people with PD: visual cueing and auditory cueing.

Visual cueing uses spatial cues, such as lines or markers on the floor, which have been shown to increase stride length, stride length regulation, and gait velocity in people with PD (Lim 2005). The most effective cues are perpendicular to the walking path and spaced one step length apart (Lewis 2000). Although the exact cause of the marked change is not known, it has been suggested that visual cues may either trigger a step, draw attention to the stepping process, provide dynamic visual feedback (Azulay 2006; Azulay 1999) or some combination of the above.

Auditory cueing, also known as rhythmic auditory stimulation, has been shown to increase cadence and velocity during locomotion (McIntosh 1997). Auditory cues can be a metronome, music with a distinct steady beat, or even nursery songs. It has been suggested that the auditory cueing provides an external rhythm that compensates for the defective internal rhythm of the basal ganglia. As with visual cueing, auditory cueing could also be drawing attention to the stepping process.

Visual and auditory cues have only been shown to improve gait parameters. This may due to the ease of testing these paradigms for gait; it is easy to place markers on the floor or to ask a participant to walk to the beat of a metronome. Gait is also a volitional daily activity that is performed regularly and repetitively; but other than gait, there is no routinely performed volitional upper body movement as regular and repetitive as gait.

Our work utilizes visual targets (visual cues) and visual feedback to provide participants with information on limb placement and limb velocity. Our goal is to characterize the motor deficit and identify if these types of visual cues and feedback is appropriate Parkinson's rehabilitation.

2.3. Interactive Technology

In Parkinson's disease, there is a growing interest in using interactive technology to guide or facilitate rehabilitation and to perform clinical evaluations. There have been few studies showing interactive technology being used to facilitate long-term rehabilitation in Parkinson's disease.

In a head mounted virtual reality system developed by Albani (2009), participants were asked to use a joystick to navigate through simulated environments (supermarket, gymnasium, kitchen, classroom, hallway, doorway, etc.) (Albani 2002; Albani 2009). In this study, participants had difficulty moving through doorways and narrow hallways. In addition, some participants had adverse effects such as hallucinations (e.g., seeing children in desks, animals on the wall) during the off cycle of medication (Albani 2009).

There have been a few other attempts at using different forms of media to encourage movement in PD, including: use of eyeglasses to project a floor grid (Ferrarin 2004) and silhouette painting (Camurri 2003). Based on information provided in the reports, both systems appeared to be in the preliminary stages.

2.4. Gaming Technology

Recent developments in video game technology have made significant advancements in motion capture capability. Depending on the system, games can provide feedback and modify interaction based on the gamer (or the game controller) position, velocity or linear/angular acceleration. The current game systems on the market are: the Wii™ Console (released

November 2006), the PlayStation® 3 Move (released September 2009), and the XBox 360® + Kinect™ (released November 2010).

The Wii™ motion technology relies on accelerometers (in the Wii™ remote) and gyroscopes (in the Wii™ MotionPlus Expansion) to detect real-time linear/angular acceleration. The Wii™ system cannot provide any feedback on the physical location of the Wii™ remote; it does not know where in the room the Wii™ remote is. The Wii™ system can however, detect when/where the Wii™ remote is being pointed (with reference to the Wii™ sensor bar). The Wii™ remote contains an infrared camera at the tip of the remote that can sense the location of the Wii™ sensor bar (essentially an array of IR LEDs). The Wii™ remote can also vibrate to convey information to the gamer; this feature is often used to identify when two onscreen objects (one representing the remote) collide.

In the PlayStation® 3, a video camera is used to track a glowing ball at the tip of a motion controller. The location and the size of the glowing ball provide the system with 3-dimensional positional information. The glowing ball can glow in a full range of color using RGB light emitting diodes. The motion controller also uses accelerometers, gyroscopes and magnetometer. The accelerometer and gyroscope provide the system with information the linear and angular acceleration. The magnetometer, used to determine the motion controller relationship with the Earth's magnetic field, is used to correct for cumulative drift from the other sensors and dead reckoning. Dead reckoning is used to track the position of the motion controller position when it is out of the view of the video camera. The motion controller, like the Wii™ remote, can also vibrate to convey information to the gamer.

The XBox 360® + Kinect™ motion technology relies on a three-camera system to track motion in 3-dimensional space. A color camera is used for image recognition. Two monochrome cameras placed a few inches apart are used to perform the 3-dimensional tracking. Since the system relies solely on cameras, more space is required for interaction than with the Wii™ and PlayStation® 3. In addition, since no controller is required there is no tactile feedback.

Although significant advancements have been made in gaming technology, the games currently on the market may not be optimal for use by the elderly or people with disabilities. Our research will focus on identifying feedback and interactions that can promote movement in participants with PD. Rather than using one of the game consoles currently on the market, our systems have been designed using a web-cam connected to a computer to facilitate implementation and to provide an easy mechanism for saving data.

CHAPTER 3

INTERACTIVE REHABILITATION SYSTEM

In this chapter we present two interactive rehabilitation systems, Figure 5, which we have developed: the Limb Placement Feedback System (Section 3.1) and the Limb Velocity Feedback System (Section 3.2). These systems utilize visual feedback and visual targets to encourage accurate limb placement and variations in velocity of movement, respectively. These systems were designed with consideration of the current gaming technology and for eventual development into systems that could be used in the home. A laboratory-based version of the system has been implemented and a feasibility study has been performed on participants with Parkinson's disease.

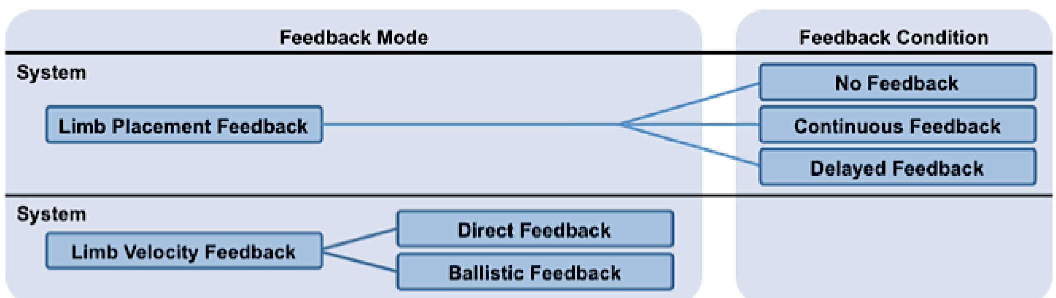


Figure 5. System Feedback Modes and Conditions. Limb Velocity Feedback has two feedback modes: Direct and Ballistic; each Velocity trial will utilize one of the two feedback modes. Limb Placement Feedback has a single feedback mode and three feedback conditions; each Placement trial may utilize one or multiple feedback conditions.

The interactive systems were designed to require minimal hardware. The system uses an infrared camera (30 fps), an infrared emitter, a projector, a projection screen, a desktop computer, custom-designed software, and a monitor to produce the interactive environment for the participant (see Figure 6). For our system, we used an IIDC FireWire Digital Camera v 1.04 (Unibrain Inc., San Ramon, California) with a 640x480 resolution. The camera was fitted with an IR filter, 87 Infra-Red (LEE Filters, Hampshire, UK), used to absorb visible light that begins transmission at 730 nm.

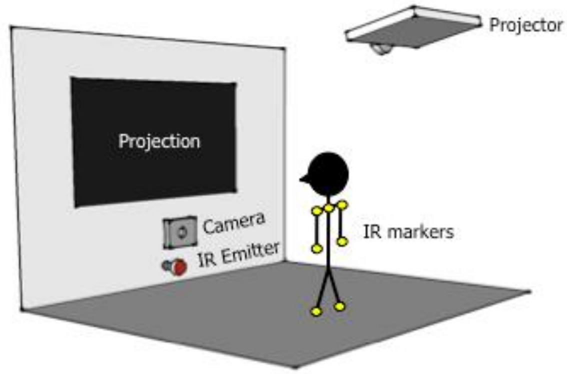


Figure 6. System Hardware Setup. The system contains projector, infrared (IR) camera, and IR emitter all connected to a desktop computer. During the study, the IR emitter is used to light up IR markers worn by the subject. The IR marker images are captured by the IR camera, parsed, and used to provide visual feedback to the participant.

3.1. Mode 1: Limb Placement Feedback

In the Limb Placement Feedback task, Figure 7, participants are asked to move their hand to the virtual targets on the screen and hold until the targets dims. Movements are made through abduction and adduction at the shoulder. The goal of the system is to encourage accurate limb placement using visual feedback.

a b c

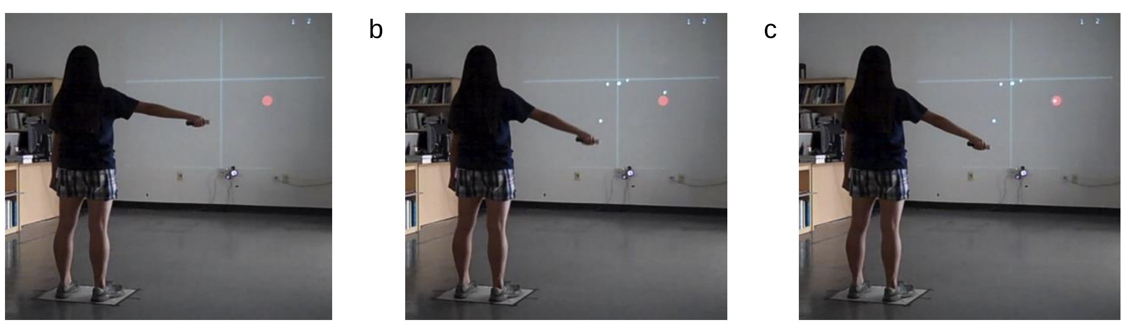


Figure 7. Limb Placement Feedback System. During the study, participants are asked to wear 7 retroreflective markers: one in the center of the chest, one on each shoulder, one on each foot, and one (on a stick) in each hand. Using those retroreflective markers, participants are asked to move their hand to virtual targets (shown in bright red) on the screen and hold until the target dims. During some reaches (or parts of the reach) participants are able to see the hand location on the screen (feedback, the retroreflective markers or white dots); while at other times, participants are unable to see their hand location (no feedback).

3.1.1. Graphics

3.1.1.1. Scaling. The projected image of each subject was scaled so that the shoulder height was the same for all subjects on the screen. The size of the target on the screen, described in Section 3.1.1.2, appeared the same for all subjects (it was not adjusted for scaled shoulder height or arm length). As a result, there was some variability in the target tolerance for each subject. The tolerance in target area ranged from 6.85 to 8.83°.

3.1.1.2. Virtual Targets. Virtual targets are represented using large circular dots projected on the screen. These dots are calibrated to the participant's anthropomorphic dimensions. Default targets are placed at R0 (rest), 45, 60, 90, 120, 135, and 150°. The location and appearance order of these dots are controlled by the experimenter/therapist.

3.1.1.3. Mapping. When using the system participants wear 7 IR retroreflective markers: one in the center of the torso, one on each shoulder, and one on each foot. In each hand they hold a short stick with a retroreflective marker on the tip; the stick was used to extend the retroreflective marker away from the hand and minimize occlusion.

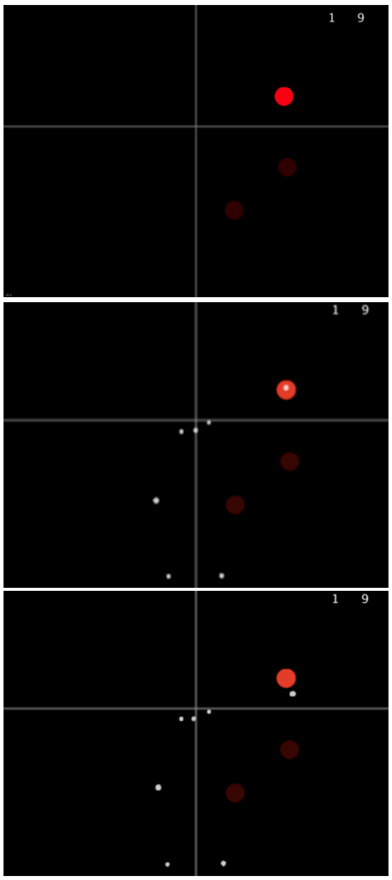
The marker images are captured using IR camera and filtered using background subtraction. Depending on the type of the feedback being used, participants may or may not be able to see the marker images on the screen.

3.1.2. Types of Feedback

This system has three different types of feedback conditions, shown in Figure 8: no feedback (N), continuous feedback (C), and delayed feedback (D). The task can be performed in a unilateral mode, in which targets are presented on one side only, or in bilateral mode, in which targets are presented on both sides and the participant is required to move both arms.

In all three conditions, participants are asked to move to the target location and hold until the target dims and a new target appears.

During the no feedback (N) condition participants are able to see the target location, but receive no feedback about the location of the IR markers. During continuous feedback (C) participants are able to see the target and the location of the IR markers. During delayed feedback (D), participants are able to see the target location, but not the location of the IR markers; and after a set delay time, participants are able to see the location of the IR markers and correct their limb placement (if necessary).



N

<u>N</u>o Feedback (N):

- Participants are able to see target.
- Participants are not able to see the IR markers.

C

<u>C</u>ontinuous Feedback (C):

- Participants are able to see target.
- Participants are able to see the IR markers

D

<u>D</u>elayed Feedback (D):

<u>Pre-Feedback:</u>

- Participants are able to see target.
- Participants are not able to see the IR markers

<u>Feedback (after preset delay):</u>

- Participants are able to see the IR markers and **correct** their reach.

Figure 8. Feedback Conditions for the Limb Placement Feedback. During each task, participants are asked to move to target location and hold until the target dims and a new target appears. Participants receive either: No Feedback (N), Continuous Feedback (C), or Delayed Feedback (D). The above image is the image seen on the projection by the subject. The virtual target is shown in bright red. The white dots are the IR markers worn by the participant.

3.2. Mode 2: Limb Velocity Feedback

In the Limb Velocity Feedback task, Figure 9, participants are asked to swing their arm up and down in the parasagittal plane. Participants receive either direct feedback or ballistic feedback. In the direct feedback mode, the instantaneous upward velocity of their arm swing is mapped to the width of a bar; participants are asked to adjust their speed place the peak width of the bar in a target zone. In the ballistic feedback mode, the instantaneous upward velocity is used to determine the exit velocity of particles flowing from a simulated fountain; participants are asked to adjust their speed to keep the height of the fountain in the target zone. Both systems can be used in either unilateral or bilateral mode.

a b

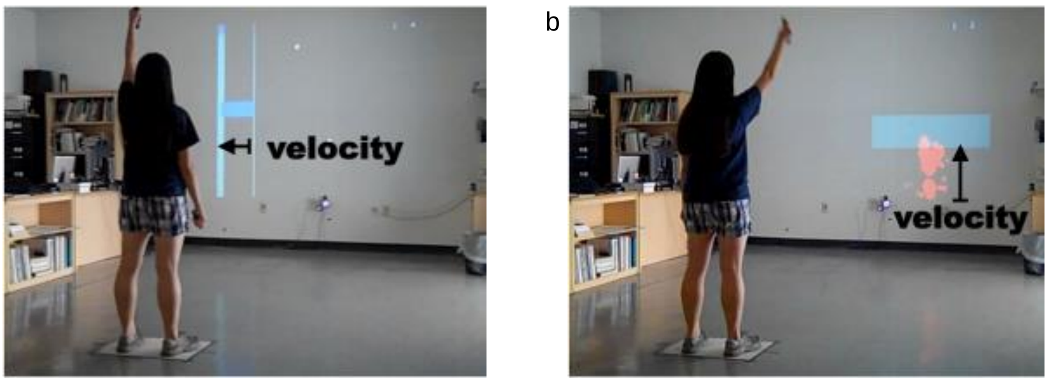


Figure 9. Limb Velocity Feedback System. During the study, participants are asked to swing their arm up and down to match the velocity target. In the direct feedback mode (a), the instantaneous y-velocity is mapped to the width of rectangle. In the ballistic feedback mode (b), the instantaneous y-velocity is mapped to the output velocity of the fountain.

3.2.1. Graphics

The system was designed for unilateral or bilateral (reciprocal) vertical arm swings. Direct and ballistic mapping was used to provide feedback on the velocity of arm swing.

3.2.1.1. Scaling. The projected image of each subject was scaled so that the shoulder height was the same for all subjects on the screen.

3.2.1.2. Mapping. When using the system participants hold two sticks with retroreflective markers on the tips, one in each hand. The marker images are captured using the IR camera and filtered using background subtraction. The location of the marker was used to calculate the real-time velocity of the retroreflective marker. The real-time velocity was calculated as the moving average of the last 9 frames. The real-time velocity was used to provide velocity feedback, as described in the next section.

3.2.1.3. Target. Target lines were used to depict target velocity. When using the system participants are asked to increase/decrease their movement velocity to reach target line. The target lines were calibrated to 100% of As Fast As Comfortable speed. The width of the target line can be increased or decreased to influence task difficulty. During the study, the tolerance was set at ±10% of As Fast As Comfortable Speed.

3.2.1.4. Automation of Target Sequence. This system has three preset targets sequences: 1) 100/80/90/110/100, 2) 100/90/110/80/100 and 3) 100/110/80/90/100 percent of As Fast As Comfortable speed. During the interaction, the system changes the target to the next target in sequence every 10 seconds (or at experimenter/therapist specified interval).

3.2.1.5. Amplitude of Feedback. Although the main purpose of this system is to provide velocity feedback, the system also gives feedback on amplitude of movement. During the interaction, if the participant does not make the full range of motion the velocity feedback will dim and eventually go dark. For the feedback to return to its normal color, participants must start making the full range of motion.

3.2.2. Types of Feedback

The Limb Velocity Feedback system was designed with two different types of feedback: direct feedback and ballistic feedback.

3.2.2.1. Direct Feedback. In the direct feedback mode, participants are given visual feedback that is proportional to the velocity of their movement. The instantaneous velocity in the vertical direction is mapped to the width of rectangle.

3.2.2.2. Ballistic Feedback. In the ballistic feedback mode, the instantaneous velocities of the participants' movement are mapped to the output velocity of a particle system emulating water fountain. As a result, the trajectory (of each particle) in the fountain is a parabolic mapping based on a ballistic equation. As the person moves faster, the spray of the fountain increases.

Given downward acceleration (i.e. gravity), the ballistics of an object is determined by [1] and [2], where $a = g = -9.8 m/s^2$, $y_0 = 0$ and $x_0 = 0$. The vertical maximum [4] is given when [3]=0.

$$y = \frac{1}{2}at^2 + vt + y_0 \tag{1}$$

$$x = vt + x_0 \tag{2}$$

$$y'(t) = at + v \tag{3}$$

$$y_{\max} = -\frac{1}{2}\frac{v^2}{g},\ t = -\frac{v}{a} \text{ when } y'(t) = 0 \tag{4}$$

The velocity in the vertical direction is mapped to a particle system projecting up from the bottom of the screen. The faster the participant swings their arm, the higher the particle system will project.

CHAPTER 4

STUDY WITH PARKINSON'S PARTICIPANTS

To address the set of hypotheses listed Section 1.1, we performed a study with a group of participants with PD and two groups of control participants (age-matched and young able-bodied). The purpose of the study was to characterize the performance of subjects in each group and to compare performance across groups.

In this study, each participant completed two sessions: the first session with the Limb Placement Feedback System and the second session with the Limb Velocity Feedback System. Enrollment of subjects for the various groups was interleaved over the course of several months.

4.1. Study Participants

4.1.1. Inclusion/Exclusion Criteria

To be included in the study, participants had to meet the following criteria:

Inclusion

1. Age between 60 and 75 years.
2. Ability to stand and walk without assistance.
3. Exhibit idiopathic Parkinson’s disease according to United Kingdom brain bank criteria.
4. Stable dosage of Parkinson’s disease medication for the 4 weeks prior to the study.

Exclusion

5. Rating of 4 or greater on any of the following items: 23, 24, 25, or 26 of the UPDRS. (Finger Taps, Hand Movements, Rapid Alternating Movements of Hands, or Leg Agility)
6. Rating of 1 or greater on item 30 of the UPDRS. (Postural Instability)
7. Prominent dyskinesia that may impair the ability to participate in the study.
8. Prominent on/off fluctuation that may result in large changes in symptoms over the course of a 2-3 hour session.
9. Presence of dementia as defined by Diagnostic and Statistical Manual of Mental Disorder-IV criteria (a score of 23 or lower on the Mini Mental Exam).

10. Inability to obtain clearance from primary care physician or cardiologist to participate in the study.
11. Presence of significant motor fluctuations.
12. Presence of significant freezing of gait.
13. Presence of significant falls.
14. Significant cardiopulmonary issues.
15. Recent history of heart disease.
16. Recent history of lung disease.
17. Any history of epilepsy.
18. Untreated chemical addiction or abuse.
19. Major neurological problem other than Parkinson's disease.
20. Major musculoskeletal problems (such as Rotator cuff).
21. Major metabolic problems (such as diabetes).
22. Evidence of pregnancy.
23. Uncorrected vision.
24. Failure to sign Informed Consent Form.

Participants with PD must fit all inclusion and no exclusion criteria.

Age-matched controls must fit inclusion criteria 1-2 and exclusion criteria 14-24.

Young Able-Bodied participants must fit inclusion criteria 2, exclusion criteria 14-24, and be between the age of 18 and 35.

4.2. Testing Procedures

4.2.1. Mode 1: Limb Placement Feedback

During the first session participant interacted with the Limb Placement Feedback System (see Section 3.1). During each trial, participants reached from the rest position toward virtual targets with either: no feedback (N), continuous feedback (C) or delayed feedback (D) of the position of the IR markers in their hand. During pre- and post- training evaluation, participants reached toward targets at the angles of 45, 60, 75, and 90° with no feedback (N). During training, participants reached toward targets at the angles of 30, 60, and 90° with either continuous feedback (C) or delayed feedback (D). Pre-training evaluation trials were used to characterize the ability to place the limb accurately by making movements at the shoulder. Post-training evaluation and training trials were used to assess short-term effects (and improvements) of training in each group.

Pre- and post- training trials consisted of 6 reaches alternating between two different targets for a total of 3 reaches (N-N-N) per targets. Each reach was from the rest position to the target.

Training trials consisted of two sets of 5 reaches: 5 reaches to one target and then 5 reaches to a second target. Each reach was from the rest position to the target. In some sets (CDDDD), the participant received continuous feedback (C), during the first reach and then delayed feedback (D) during the next four reaches. In other sets (DDDDD), the participant received delayed feedback during each reach. Sequences of reaches were designed to enhance learning by first providing continuous feedback to maximize the likelihood of success and then providing delayed feedback to challenge the participant then give them the opportunity to adjust to actual target location. All LPF trials (pre-training, training, and post training) can be seen in Table 2.

Table 2. LPF Task Order

Trial	Task	Target Location 1	Target Location 2	Feedback
1	Pre-	45	75	N-N-N
2	Pre-	60	90	N-N-N
3	Training	60	30	CDDDD
4	Training	90	60	CDDDD
5	Training	30	90	CDDDD
6	Training	60	30	DDDDD
7	Training	90	60	DDDDD
8	Training	30	90	DDDDD
9	Post-	45	75	N-N-N
10	Post-	75	105	N-N-N

Note. For the participants with PD, the tasks listed above were performed on the least affected hand (primary, or U1°), most affected hand (secondary, or U2°), and then bilaterally. For the age-matched and young groups, the tasks were performed first on the side of the dominant hand (primary, or U1°), then the side of the non-dominant hand (secondary, or U2°), then bilaterally.

During all tasks, the participant's peripheral view was occluded to ensure they did not use direct visual observation of their arm movement to guide their movement; their foveal view remained intact. This was done using a baseball cap with a cloth that hung vertically from the visor to block the view of the periphery.

4.2.2. Mode 2: Feedback of Amplitude of Velocity

Participants were asked to swing their arm up and down and match onscreen velocity targets. Target speeds were normalized to their maximum comfortable speed or As Fast As Comfortable. The onscreen target speeds were set at 80, 90, 100 or 110% of As Fast As Comfortable speed. The order of the targets was randomized into three different target sequences, listed in Table 3.

Table 3. Limb Velocity Feedback Protocol – Target Sequence Order

Target Order	1	2	3	4	5
Sequence 1	100	80	90	110	100
Sequence 2	100	90	110	80	100
Sequence 3	100	110	80	90	100

Note. This table contains the location of the targets for each sequence. Each sequence consisted of 5 targets: 80, 90, 100, 100, and 110% of As Fast As Comfortable Speed.

This task was performed on the least affected side, most affected side and then bilaterally in a reciprocal manner. Each subject first performed the trials with the direct feedback paradigm and then performed the trials with the ballistic feedback paradigm. Calibration trials, in which the participant will be asked to swing their arms As Fast As Comfortable, was performed at the beginning and end of each session. The sequence of tasks to be used is listed in Table 4.

Table 4. Velocity Mode: Intervention Task Description

Trial	Side	Sequence Order
AFAC	Least	x
AFAC	Most	x
AFAC	Bilateral	x
Direct	Least	1,2,3
Direct	Most	2,3,1
Direct	Bilateral	3,1,2
Direct	Least	1,2,3
Direct	Most	2,3,1
Direct	Bilateral	3,1,2
Ballistic	Least	1,2,3
Ballistic	Most	2,3,1
Ballistic	Bilateral	3,1,2
Ballistic	Least	1,2,3
Ballistic	Most	2,3,1
Ballistic	Bilateral	3,1,2
AFAC	Least	x
AFAC	Most	x
AFAC	Bilateral	x

Note. Sequence of targets shown in Table 3.

4.3. Data Processing

4.3.1. Mode 1: Limb Placement Feedback

During the Limb Placement Feedback tasks, participants were asked to move their hand to the virtual targets and hold until the target dimmed. During each trial, participants were given a sequence of feedback and no feedback conditions (N – No Feedback, C – Continuous Feedback, D – Delayed Feedback): NNN, CDDDD, DDDDD. Shown in Figure 10 is a sample trial.

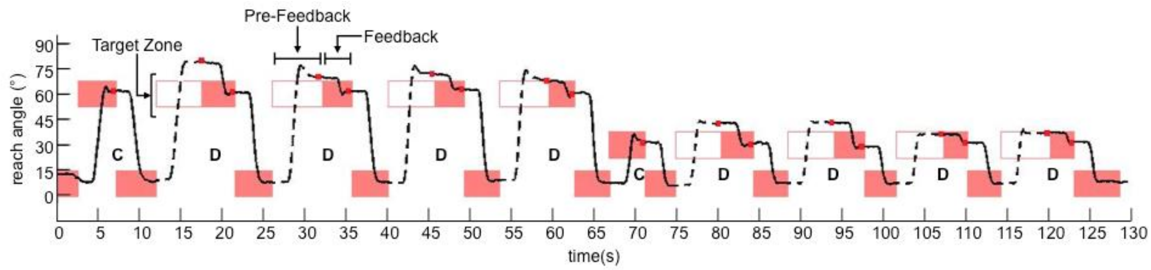


Figure 10. Sample Limb Placement Feedback Trial. In this trial, the targets were located at 60 and 30°; the feedback sequence was CDDDD - Continuous Feedback, Delayed Feedback, and Delayed Feedback. The location of the hand was calculated as the mean of the last 0.5 sec that the target was displayed.

The location of the hand relative to the target was calculated as the mean of the last 0.5 sec that the target was displayed. This was calculated only for the target locations (and not the rest target).

In a few No-Feedback and Delayed Feedback cases, participants were still moving when the target changed or target appeared; these reaches were not included in the analysis. This determination was based on whether the instantaneous velocity was greater than 15°/sec for over half of the last second before the target appeared.

An example of all of the data extracted from a single session is shown in Figure 11.

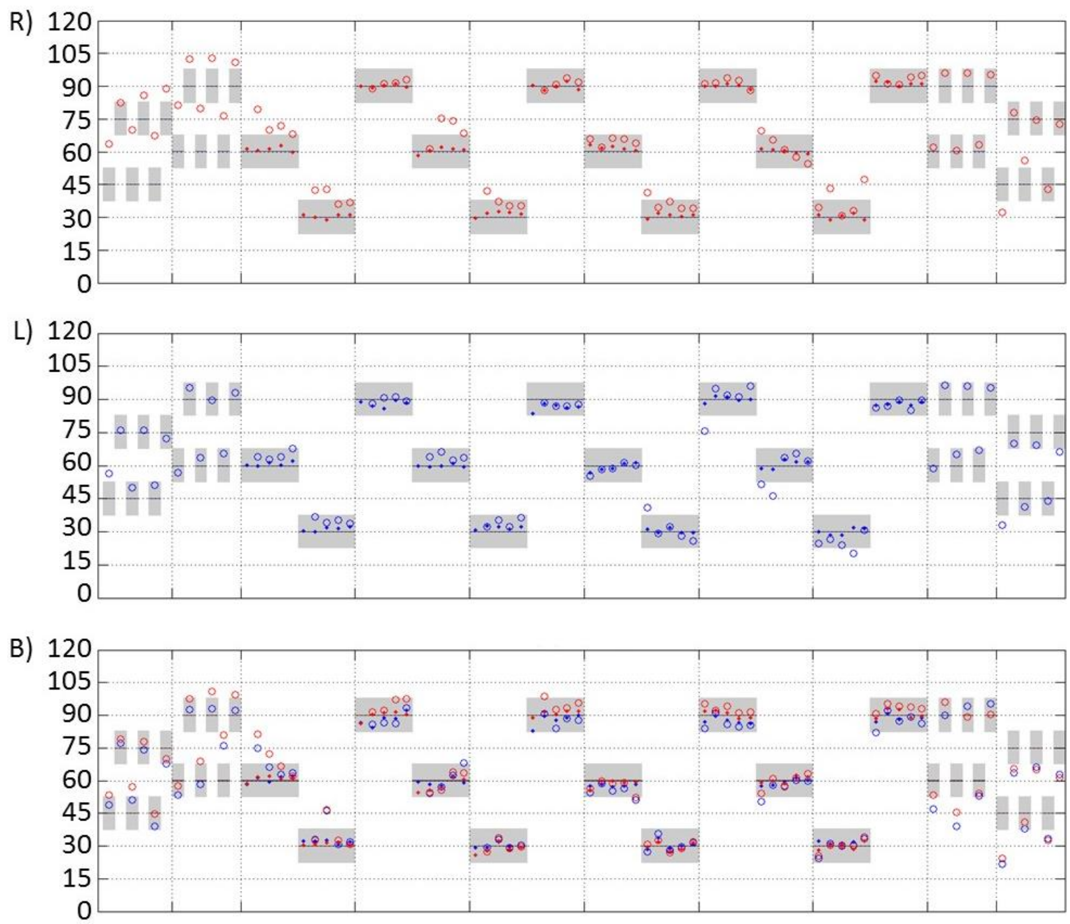


Figure 11. Sample Limb Placement Feedback Session. These data were extracted from a single session with a subject from the PD group. The open circles represent the reaches with no feedback and the filled circles represent the reaches (or adjustments) with feedback. The shaded area represents the target zone during that reach. The most affected hand for this participant (CH_PD_04) was the Left Hand, therefore the first series of reaches was performed with the right hand. The red circles represent the right hand; the blue circles represent the left hand. The subject followed the tasks laid out in Table 2.

4.3.2. Mode 2: Limb Velocity Feedback

During the Limb Velocity Feedback tasks, participants were asked to swing their arm up and down and adjust their speed to match the onscreen target. Participants were either given direct feedback or ballistic feedback. An example of the velocity profile for one trial is shown in Figure 12.

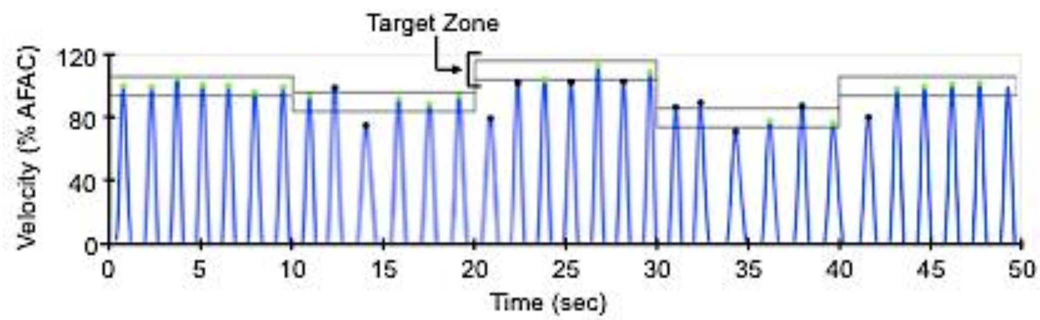


Figure 12. Sample Limb Velocity Feedback Trial. In this trial, the target sequence was 100, 90, 110, 80, and 100; each target appeared for 10 seconds before changing the next target in the sequence. The velocity of the hand was calculated with respect to the participants' As Fast As Comfortable velocity.

The peak velocity of the movement was calculated as the maximum peak value (or the peak velocity of the upward hand movement); this value was normalized to the participants' As Fast As Comfortable velocity.

4.4. Data Compilation

During the Limb Placement Task, each participant performed 10 trials of reaches for 5 different targets; not all targets appeared in all trials. For the purpose of the analysis, we refer to Target Presentation (TP) as the each time a target appeared in a trial. During the No-Feedback trials (i.e. the pre-/post- trials), the 45, 60, 75, and 90° target appeared in 2 trials: 1 pre-trial and 1 post-trial. The data for these pre- and post- trials were analyzed as a set and are referred to as the pre-trial and post-trial. During the Delayed Feedback trials, each target appeared 4 times: 2 trials of CDDDD and 2 trials of DDDDD. For these trials, each of the last 4 reaches of these trials were analyzed separately; these trials are referred to as training TP1 to TP4.

During the Limb Velocity Task, all participants performed 6 trials for each side. All targets (100A, 80, 90, 110, and 100B% of AFAC) appeared in each trial. These trials are referred to as TP1 to TP6.

4.5. Performance Indices

4.5.1. Mode 1: Limb Placement Feedback

A set of measures, shown in Table 5, was calculated for each subject for the limb placement task. The purpose of these measures was to identify any differences in the ability to control limb placement across the groups, and to characterize the effects of learning, side, and target.

Table 5. List of Placement Measures.

↓	E_{absN}	a)	Mean of the absolute error across the reaches for No-Feedback Trials (Section 4.4.1.1).
↓	E_{absD}	b)	Absolute error for each Delayed Feedback Reach (Section 4.4.1.2).
↓	Sym_N	c)	Mean of the absolute maximum deviation between the Primary and Secondary limb across the reaches for the Bilateral No-Feedback Trials (Section 4.4.1.3).
↑	V_{PeakN}	d)	Mean of the maximum peak velocity across the reaches for No-Feedback Trials (Section 4.4.1.4).
↓	T_{EarlyN}	e)	Mean of the early movement time, defined as the time it took for subject to move 10% of the entire reach trajectory, across the reaches for No-Feedback Trials (Section 4.4.1.5)
↓	T_{MoveN}	f)	Mean of the movement time, defined as the time it took for the subject to move from 10% to 90% of the entire reach trajectory, across the reaches for No-Feedback Trials (Section 4.4.1.6)
↓	$Range_N$	g)	Range of the recorded values for excursion during No Feedback trial reaches (Section 4.4.1.7).

Note. The arrow indicates the direction of favorable change.

4.5.1.1. Placement Measure Description, E_{absN}: Mean of the Absolute Error for No-Feedback Trials. The pre- and post- trials for each side consisted of three reaches with no feedback. This measure, E_{absN}, is the mean of the absolute error of those three reaches for each subject, side (U1°, U2°, B1°, B2°), target (45°, 60°, 75°, 90°), and trial (pre and post). A visual description of this measure can be seen in Figure 13a.

This measure is intended to indicate accuracy before and after training and to determine the effects of training.

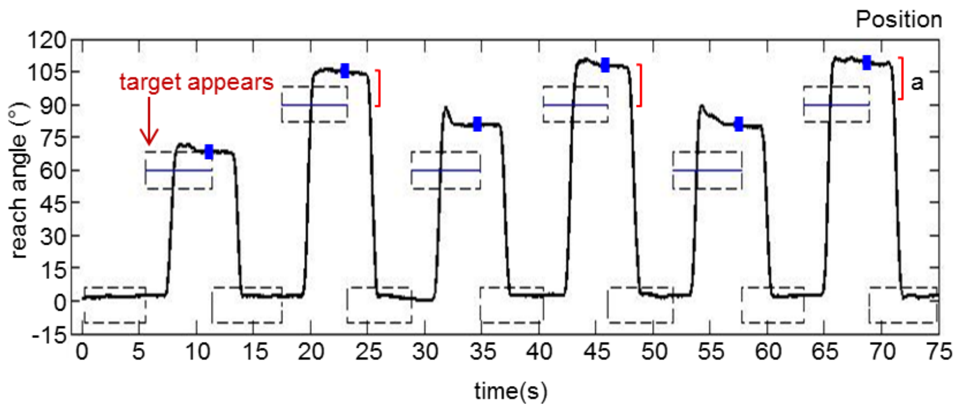


Figure 13. Placement Measure(s): a) 🡻 E_{absN}: Mean of the Absolute Error for No-Feedback Trials.

4.5.1.2. Placement Measure Description, E_{absD}: Absolute Error for Delayed Feedback Trials. For each side and each target, participants completed 4 training trials of reaches for each target; each trial consisted of 5 reaches (CDDDD or DDDDD). This measure, E_{absD}, is the absolute error of the last four reaches for each subject, side, and target; all of these reaches were done with delayed feedback. The first reach for each trial was not included in this measure as some reaches were performed with continuous feedback and some reaches were performed with delayed feedback.

This measure was performed for each side (U1°, U2°, B1°, B2°), each target (30°, 60°, 90°), and each training TP (1-4). A visual description of this measure can be seen in Figure 14b. This measure is intended to indicate the effects of training.

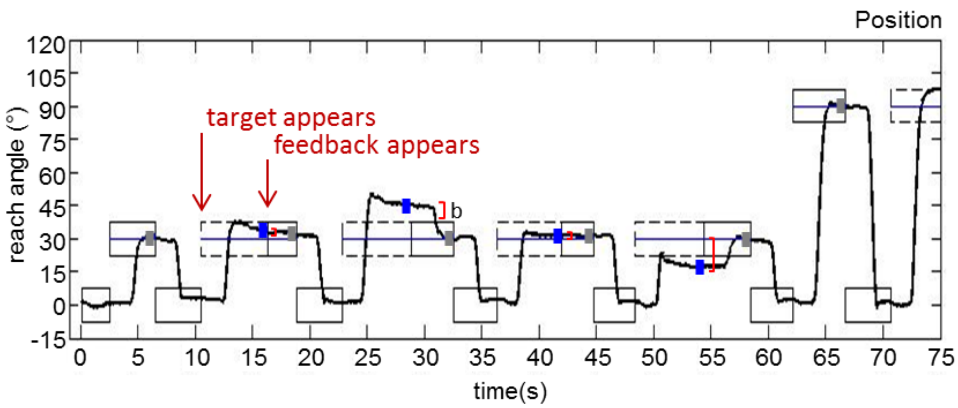


Figure 14. Placement Measure(s): b) ➜ E_{absD}: Absolute Error for Delayed Feedback Trials.

4.5.1.3. Placement Measure Description, Sym_N: Symmetry. This measure was performed on the pre- and post- trial for the bilateral condition. Symmetry was calculated as the absolute difference between the primary and secondary limb at the end of each reach. This measure, Sym_N, is the mean of the absolute symmetry for each subject, each target (45°, 60°, 75°, 90°), and trial (pre and post). A visual description of this measure can be seen in Figure 15c.

For people with PD, asymmetry of movement or angle matching has been characterized in the elbow. This measure is intended to characterize the symmetry (or lack thereof) in movements of the shoulders.

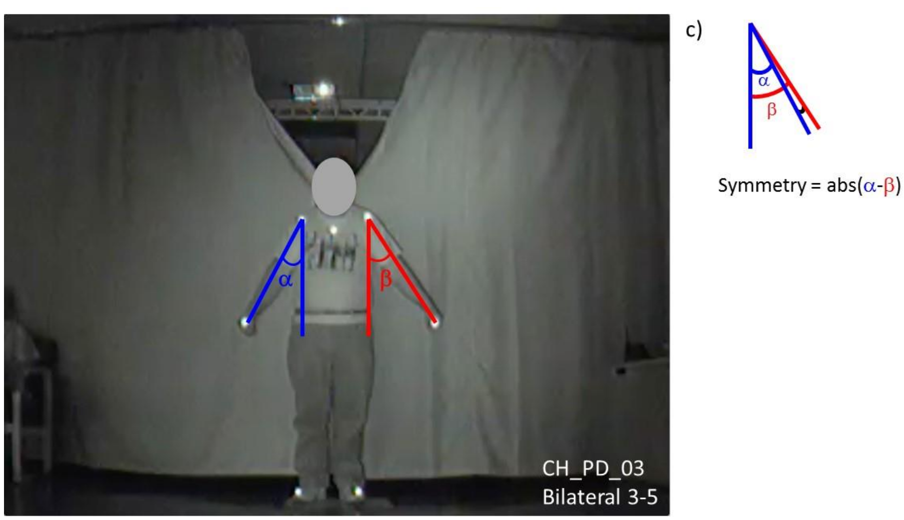


Figure 15. Placement Measure(s): c) ➜ Sym_N: Symmetry for No-Feedback Trials.

4.5.1.4. Placement Measure Description, V_{PeakN}: Velocity Peak. This measure was performed on the pre- and post- trial for each side. The velocity peak was calculated as the maximum peak velocity for each reach. This measure, V_{PeakN}, is the mean of the maximum velocity peak for each subject, target (45°, 60°, 75°, 90°), each side (U1°, U2°, B1°, B2°), and trial (pre and post). A visual description of this measure can be seen in Figure 16d.

Generally, subjects exhibit higher movement speeds as they move to more distant targets. Parkinson's disease is characterized by slower movement or bradykinesia. This measure is intended to characterize the speed of movement and to determine if people with PD are able to adjust their movement speed.

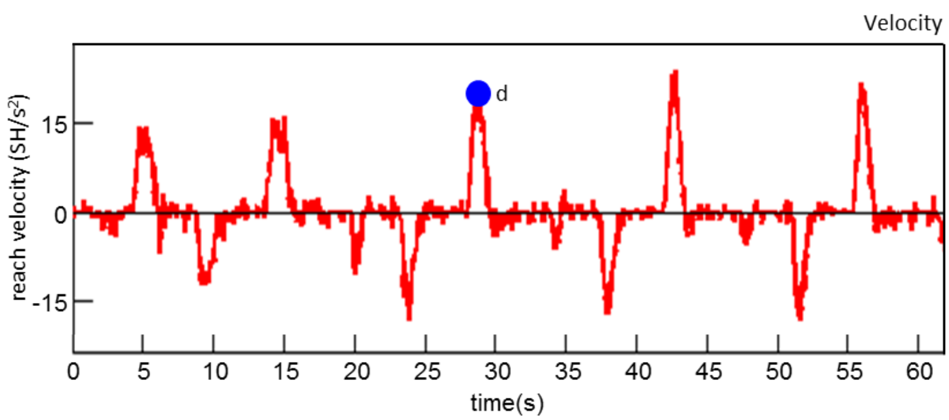


Figure 16. Placement Measure(s): d) ↑ V_{PeakN}: Velocity Peak for No-Feedback Trials.

4.5.1.5. Placement Measure Description, T_{EarlyN}: Early Movement Time. This measure was performed on the pre- and post- trial for each side. The early movement time was calculated as the time it took for the subject to move 10% of the entire reach (or the reaches maximal position). This measure, T_{EarlyN}, is the mean of the early movement time for each subject, each target (45°, 60°, 75°, 90°), each side (U1°, U2°, B1°, B2°), and trial (pre and post). A visual description of this can be seen in Figure 17e.

People with PD often have difficulty initiating movement, akinesia; this measure is intended to indicate the amount of time it took a subject to initiate movement

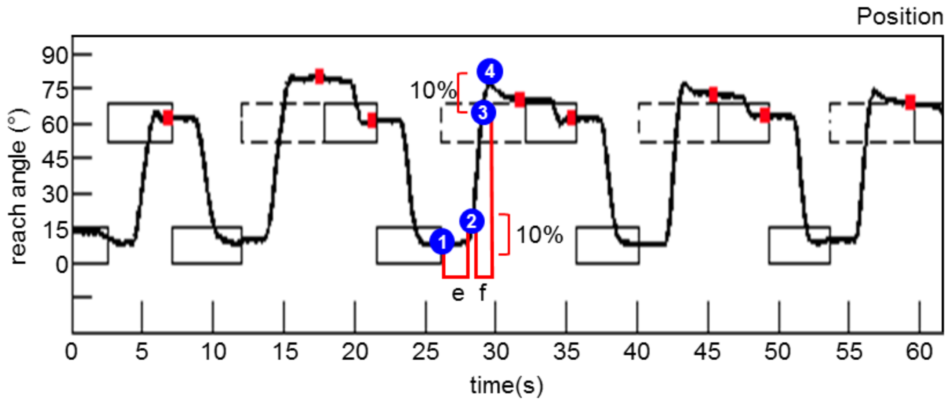


Figure 17. Placement Measure(s): e) ➜ T_{EarlyN}: Early Movement Time and f) ➜ T_{MoveN}: Movement Time for No-Feedback Trials. The rest target disappears and the reach target appears on (1). The entire reach is defined as (1) to (4), where (4) is the maximum peak position of the reach. (2) and (3) are defined as 10% and 90% of the entire reach.

4.5.1.6. Placement Measure Description, T_{MoveN}: Movement Time. This measure was performed on the pre- and post- trial for each side. The movement time was calculated as the time it took for the subject to move from 10% to 90% of the entire reach (or the reaches maximal position). This measure, T_{MoveN}, is the mean of the movement time for each subject, each target (45°, 60°, 75°, 90°), each side (U1°, U2°, B1°, B2°), and trial (pre and post). A visual description of this measure can be seen in Figure 17f.

Parkinson's disease is characterized by slower movement, or bradykinesia. This measure is intended to characterize the time that it took to make the movement, which can be used to determine whether people with PD take longer to reach a target than the other groups.

4.5.1.7. Placement Measure Description, $Range_N$: Range for No-Feedback Trials. The pre- and post- trials for each side consisted of three reaches with no feedback. This measure, $Range_N$, is defined difference between the maximum and minimum of the movement amplitudes recorded during those three reaches. A visual description of this measure can be seen in Figure 18g.

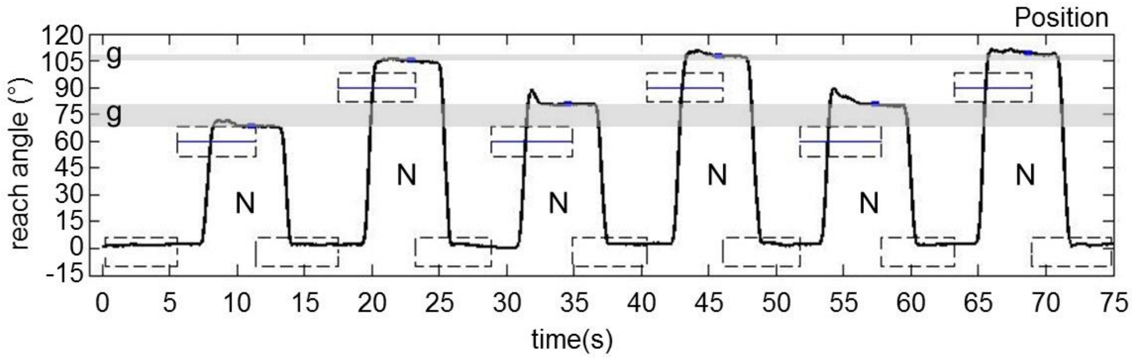


Figure 18. Placement Measure(s): g) ↓ $Range_N$: Range of No-Feedback Trials.

4.5.2. Mode 2: Limb Velocity Feedback

A set of measures, shown in Table 6, was calculated for each subject for the limb velocity task (listed below). The purpose of these measures was to look at the effects of Parkinson's disease on participant's ability to produce movements at different speeds. For each measure, we looked at the differences between groups, the effects of learning, side, and target.

Table 6. List of Velocity Measures.

↑	Acc	a)	Accuracy: percentage of swings inside the target area.
↑	Tot	b)	Total number of swings per target.
↑	Exc	c)	Mean of the excursion, length of swing relative to shoulder height, for each target.
↓	Std_{aPeakx}	d)	Standard deviation of the peak position of the swing for each target in the lateral direction.
↓	Std_{aPeaky}	e)	Standard deviation of the peak position of the swing for each target in the vertical direction.
↑	Recip	f)	The coefficient of determination, R^2, of the trajectory of primary and secondary limb during the bilateral task.
↑	Sym	g)	The ratio of the time between the peak velocities of the primary and secondary limb during the bilateral task.
↓	Dev_{Mid}	h)	The mean lateral deviation of each swing for each target, at the midpoint of the swing, relative to the lateral peak and valley of that swing.
↓	Dev_{HL}	i)	The mean lateral deviation between the peak and valley of each swing for each target.
↓	$Hull_{Area}$	j)	Area of the hull created from the swing trajectory for a single trial plotted in the coronal plane.
↓	$Hull_{Width}$	k)	Width of the hull created from the swing trajectory for a single trial plotted in the coronal plane.

Note. The arrow indicates the direction of favorable change.

4.5.2.1. Velocity Measure Description, Acc: Accuracy. For each trial, subjects were asked to swing their arm up and down and to adjust their speed to hit onscreen targets. Each target had a tolerance of ±10% of the As Fast As Comfortable (AFAC) speed and was on the screen for 10 seconds. This measure, Acc, is the percentages of swings inside the target range. This measure was performed for each subject, each side (U1°, U2°, B1°, B2°), each trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 19a.

This measure is intended to indicate accuracy for each trial.

4.5.2.2. Velocity Measure Description, Tot: Total. For each trial, subjects were asked to swing their arm up and down and to adjust their speed to hit onscreen targets. Each target was on the screen for 10 seconds. This measure, Tot, is the number of swings performed per target (i.e. with the 10 second period). This measure was calculated for each subject, each side (U1°, U2°, B1°, B2°), each trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 19b.

People with PD have been characterized with slower movement (bradykinesia). This measure is intended to see if the impairment affects the total number of swings that were performed in the time period.

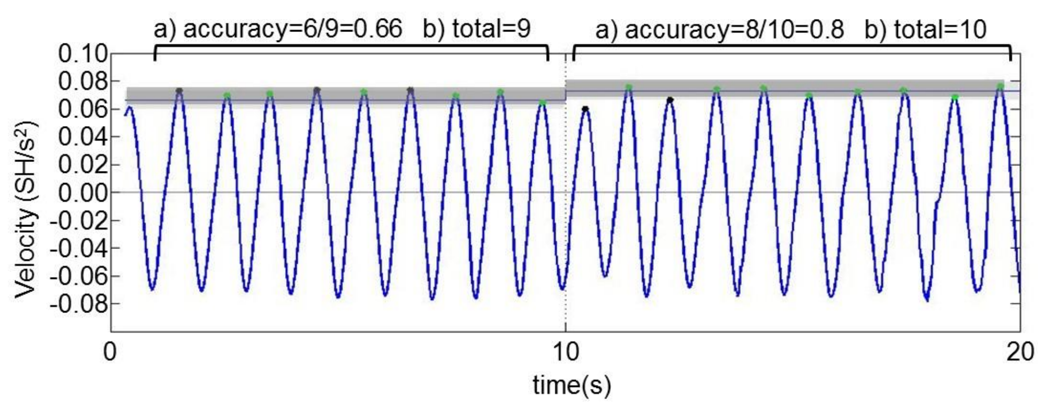


Figure 19. Velocity Measure: a) ↑ Acc: Accuracy and b) ↑ Tot: Total

4.5.2.3. Velocity Measure Description, Exc: Excursion. Excursion was calculated for each target as the total swing length relative to the shoulder height; from the start (or the minimum) of the swing to the end (or the maximum) of the swing. This measure, Exc, is the mean of all the swing excursions for a given target. This measure was calculated for each subject, each side (U1°, U2°, B1°, B2°), each trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 20c.

All subjects were asked to adjust their speed to reach the onscreen target. However, it is also possible for subjects to adjust their excursion, consciously or subconsciously, to achieve the same goal. This measure is intended to characterize if and how subjects adjusted their excursion to achieve the task.

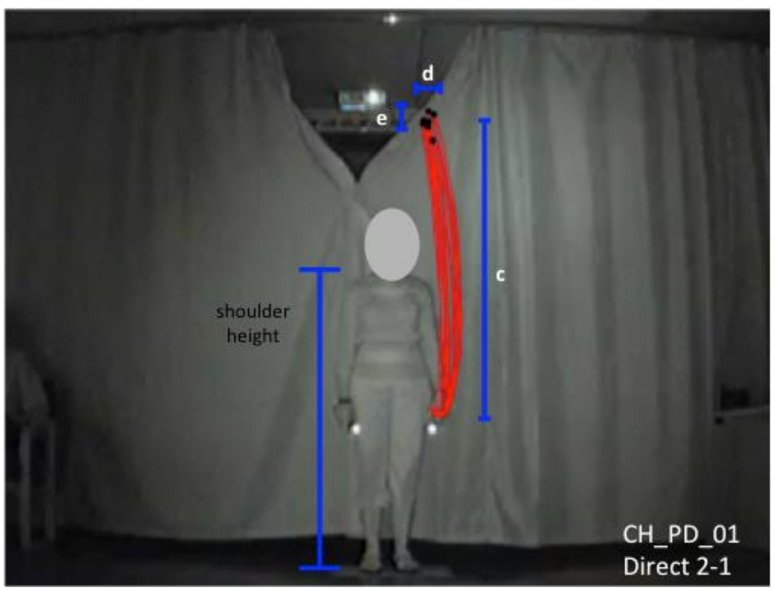


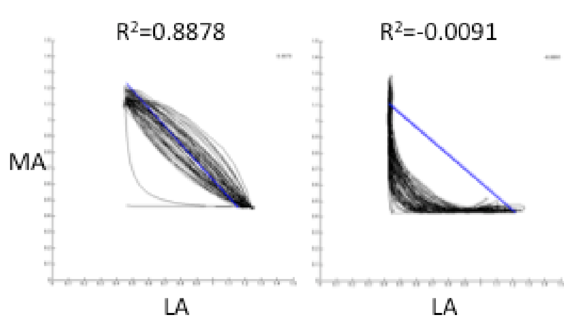
Figure 20. Velocity Measures: c) ↑ Exc: Excursion, d) ↓ Std_{aPeakX}: Standard Deviation of the Peak Position in the Lateral Direction and e) ↓ Std_{aPeakY}: Standard Deviation of the Peak Position in the Vertical Direction

4.5.2.4. Velocity Measure Description, Std_{aPeakX}: Standard Deviation of the Peak Position in the Lateral Direction. For each swing, for a given target, the lateral peak position was calculated as the horizontal position of the arm at the peak of the swing. This measure, Std_{aPeakX}, is the standard deviation of all the lateral peak positions for each target. This measure was performed for each subject, each side (U1°, U2°, B1°, B2°), each trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 20d. This measure is intended to characterize variability in the movement pattern.

4.5.2.5. Velocity Measure Description, Std_{aPeakY}: Standard Deviation of the Peak Position in the Vertical Direction. For each swing, for a given target, the vertical peak position was calculated as the vertical position of the arm at the peak of the swing. This measure, Std_{aPeakY}, is the standard deviation of all the lateral peak positions for each target. This measure was calculated for each subject, each side (U1°, U2°, B1°, B2°), each trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 20e.

4.5.2.6. Velocity Measure Description, Recip: Reciprocity. For each target of each bilateral trial, the vertical position of the secondary hand was plotted against the vertical position of the primary hand. The vertical minimum and maximum for each hand was calculated and the best-fit line was drawn for between the (B2°-min, B1°-max) to (B2°-max, B1°-min). This measure, Recip, is the coefficient of determination or R2 between the data and min-max line. This measure was calculated for each subject, for the each bilateral trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 21f.

During bilateral tasks, subjects were asked to swing one arm up as the other arm went down. Other studies have shown that people with PD sometimes have trouble with bilateral movement. This measure is intended to capture whether subjects were able to perform the task as instructed.

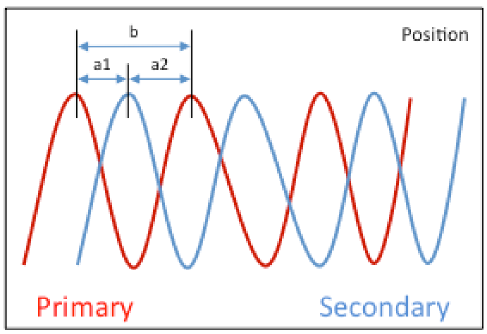


f)

Figure 21. Velocity Measures: f) ↑ Recip: Reciprocity

4.5.2.7. Velocity Measure Description, Sym: Symmetry. For each target of each bilateral trial, the symmetry was calculated as the ratio of time between two primary peaks and between the primary and secondary peak. This measure, Sym, was calculated as the mean of all the symmetries for a single target. This measure was performed for each subject, for the each bilateral trial (1-6), and each target (100A, 80, 90, 110, and 100B% of AFAC). A visual description of this measure can be seen in Figure 22g. Symmetry can range from 0 to 0.5.

In this task, during the bilateral task, the peak of a subject's secondary swing should be in the center of the subject's primary swing and vice-versa. This measure is intended to characterize the symmetry of timing of the swings.



Symmetry = min(a1,a2)/b

Figure 22. Velocity Measures: g) ↑ Sym: Symmetry. Symmetry can range from 0 to 0.5.

4.5.2.8. Velocity Measure Description, Dev_{Mid}: Mean of the Midpoint Lateral Deviation of Each Swing. For this measure, Dev_{Mid}, the difference between the lateral position of the minimum and midpoint of each swing was calculated and averaged. This measure was calculated for each subject, each side (U1°, U2°, B1°, B2°), and each trial (1-6). A visual description of this measure can be seen in Figure 23h. This measure is intended to characterize variability in the movement pattern.

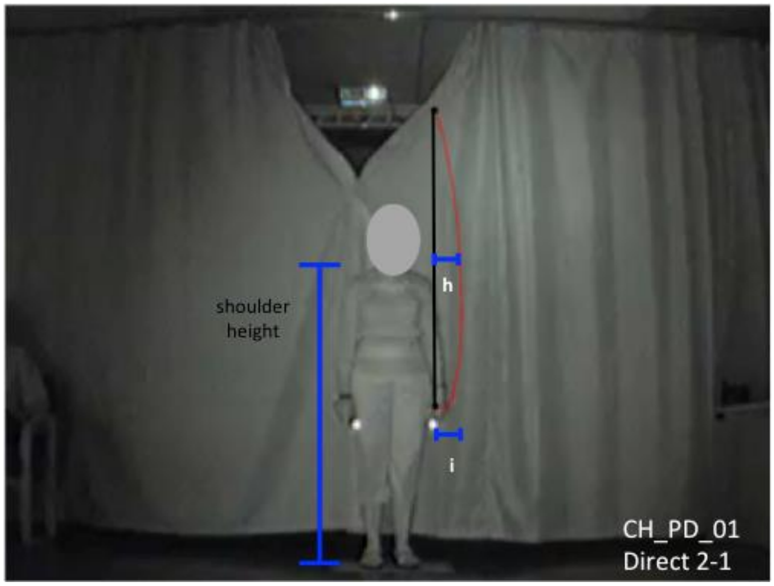


Figure 23. Velocity Measures: h) ↓ Dev_{Mid}: Mean of the Midpoint Lateral Deviation of Each Swing and i) ↓ Dev_{HL}: Mean of the Peak-Valley Lateral Deviation of Each Swing

4.5.2.9. Velocity Measure Description, Dev_{HL}: Mean of the Peak-Valley Lateral Deviation of Each Swing. For this measure, Dev_{HL}, the difference between the lateral position of the minimum and maximum of each swing was calculated and averaged. This measure was performed for each subject, each side (U1°, U2°, B1°, B2°), and each trial (1-6). A visual description of this measure can be seen in Figure 23i.

This measure is intended to characterize variability in the movement pattern.

4.5.2.10. Velocity Measure Description, $Hull_{Area}$: Hull Area. For this measure, $Hull_{Area}$, the lateral versus vertical position was plotted for each trial. The subsequent hull image was subdivided into 0.01x0.01 matrix and zeroed. By iterating through the hull line, every matrix cell containing a portion of the hull line was set to 1. The matrix cells were summed and reported. This measures was performed for each subject, each side (U1°, U2°, B1°, B2°), and each trial (1-6). A visual description of this measure can be seen in Figure 24j. This measure is intended to characterize variability in the movement pattern.

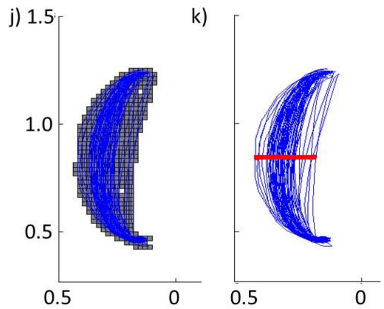


Figure 24. Velocity Measures: j) ↓ $Hull_{Area}$: Hull Area and k) ↓ $Hull_{width}$: Hull Width

4.5.2.11. Velocity Measure Description, $Hull_{Width}$: Hull Width. For this measure, $Hull_{Width}$, the lateral versus vertical position was plotted for each trial. The width of the subsequent hull was reported at the midpoint of the hull for each subject, each side (U1°, U2°, B1°, B2°), and each trial (1-6). A visual description of this measure can be seen in Figure 24j.

This measure is intended to characterize variability in the movement pattern.

4.6. Statistics

All measures described in Sections 4.4.1 (Placement Measures) and 4.4.2 (Velocity Measures) were analyzed using SPSS General Linear Model (GLM) function. Each measure was analyzed to determine differences between subject groups and to assess the effect of the factors: target, side and trial. When analyzing across factor interactions, the Bonferonni correction was used. Since, the GLM function could not be run with missing data, in the Limb Placement Feedback Analysis, missing data points had to be calculated. For the measure, E_{absD}, 2 out of 9216 data points were missing and were replaced with the average of the other reaches for that subject, side, target and trial. For the measures, E_{absN}, T_{moveN}, T_{reactN}, V_{peakN}, and $Range_N$, 1 of 1536 data points was missing. Since these measures were calculated the average of the pre- or post- trial reaches, they could not be calculated from the average of the "other" reaches. As a result, this data point, a pre- data point, was replaced with the post- data point for that subject, side, and target. This subject, for other side and targets, did not appear to have large differences in the pre- and post- values of the data.

CHAPTER 5

LIMB PLACEMENT FEEDBACK RESULTS

During the limb placement feedback protocol participants were asked to reach to a series of targets with no feedback (N), continuous feedback (C), and delayed feedback (D). The order of tasks can be seen in Table 2.

5.1. Screened Participants Characteristics

The system was tested on 15 participants with Parkinson's disease (PD), 18 Age-Matched (AM) subjects and, 16 Young-Able Bodied (YA) participants.

Three age-matched subjects were excluded from the position analysis: participant AM_02 was unable to understand the task, participant AM_06 did not finish the task, and there was a protocol deviation on participant AM_13 (AM_13 was left-handed and tasks were inadvertently performed with right-hand first).

Information about the PD participants is shown in Table 7; AM participants in Table 8, and YA participants in Table 8.

Inclusion/ Exclusion Criteria Deviations: Two participants with Parkinson's disease were outside the inclusive age range of 50 to 75. Participants PD_05 and PD_11 were 49 and 77 respectively. The medical monitors approved these participants for the study because they were very close to the age limit and the nature of their PD-related motor control impairments made them highly appropriate for the study. All other inclusion and exclusion criteria were met by all participants.

Table 7. List of Participants With PD

Subject ID	Gender	Age	Most Affected Side	H&Y	UPDRS motor
CH_PD_01	Female	69	Right	3	34
CH_PD_02	Female	62	Right	2	12
CH_PD_03	Male	65	Left	2	24
CH_PD_04	Male	74	Left	2	21
CH_PD_05	Female	49	Left	3	28
CH_PD_06	Male	69	Right	3	27
CH_PD_07	Male	67	Left	2	22
CH_PD_08	Male	65	Right	1.5	7
CH_PD_09	Female	64	Left	1	15
CH_PD_10	Male	49	Left	2	18
CH_PD_11	Male	77	Right	3	40
CH_PD_12	Male	60	Right	2	35
CH_PD_13	Male	62	Left	2	16
CH_PD_14	Male	58	Right	2	23
CH_PD_15	Male	68	Right	2	16

Table 8. List of Control (AM, YA) Participants

Subject ID	Gender	Age	Dominant Hand
CH_AM_01	Female	56	Right
CH_AM_03	Female	52	Right
CH_AM_04	Female	75	Right
CH_AM_05	Female	61	Right
CH_AM_07	Male	53	Right
CH_AM_08	Female	54	Right
CH_AM_09	Female	52	Both
CH_AM_10	Male	57	Right
CH_AM_11	Male	66	Right
CH_AM_12	Female	58	Right
CH_AM_14	Male	73	Right
CH_AM_15	Female	66	Right
CH_AM_16	Female	54	Right
CH_AM_17	Female	58	Right
CH_AM_18	Male	64	Right
CH_AM_19	Male	71	Right
CH_AM_20	Female	49	Right

Subject ID	Gender	Age	Dominant Hand
CH_YA_01	Female	22	Right
CH_YA_02	Male	21	Right
CH_YA_03	Female	35	Right
CH_YA_04	Male	26	Right
CH_YA_05	Male	28	Right
CH_YA_06	Male	25	Right
CH_YA_07	Female	25	Right
CH_YA_08	Male	19	Both
CH_YA_09	Female	22	Right
CH_YA_10	Female	19	Right
CH_YA_11	Male	29	Right
CH_YA_12	Male	25	Right
CH_YA_13	Female	19	Right
CH_YA_14	Female	21	Right
CH_YA_15	Female	32	Right
CH_YA_16	Female	28	Right

5.2. Placement Measurements

A detailed description of how the placement measures were calculated can be seen in Section 4.4.1.

5.2.1. Placement Measure Results, E_{absN}: Mean of the Absolute Error for No-Feedback Trials

During the pre- and post- trials, there were no observed differences in accuracy between the groups. However, there were observed differences between pre- and post- trials for all groups. Each group was able to place their limbs more accurately after training. The accuracy of limb placement for pre- and post- training is shown in Figure 25.

When comparing accuracy for each side, pre- and post- training, each group placed their limbs more accurately after training on the unilateral primary side (U1°). In addition, the PD group also placed their limbs more accurately on the unilateral secondary side (U2°) and both the PD and Age-Matched groups placed their limbs more accurately to the bilateral primary side (B1°). The accuracy of limb placement for each side, pre- and post- training, is shown in Figure 26.

When comparing accuracy for each target, pre- and post- training, most groups placed their limbs more accurately to all targets after training and several groups showed less accurate limb placement to lower targets. The accuracy of limb placement for each target, pre- and post-training is shown in Figure 27.

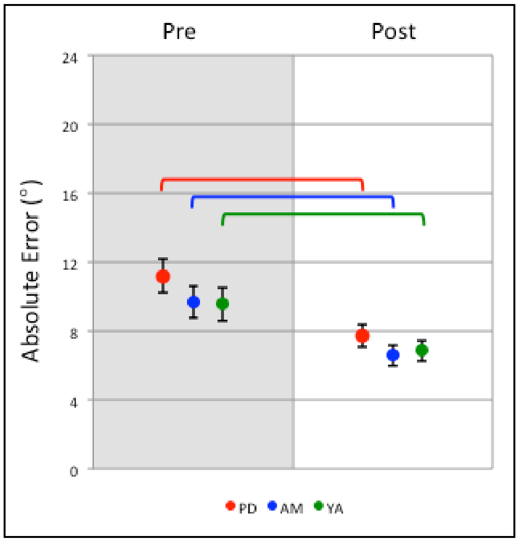


Figure 25. Accuracy of Limb Placement Pre- and Post- Training.
Placement Measure: E_{absN}. Comparison: Pre/Post. Legend: The vertical bars represents standard errors, the horizontal bars represent comparisons with significant difference, and the asterisks represent comparisons with significant difference.
a) Each group placed their limbs more accurately after training.

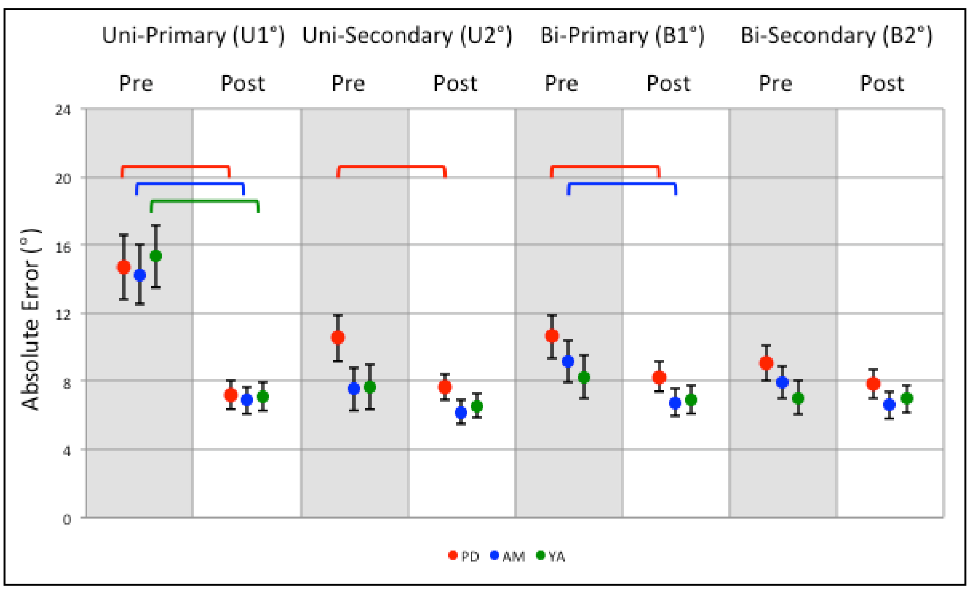


Figure 26. Accuracy of Limb Placement for Each Side, Pre- and Post- Training.
Placement Measure: E_{absN}. Comparison with Bonferroni Correction: Pre/Post−Side. Legend as described in Figure 25.
a) Each group placed their limbs more accurately after training in the U1°.
b) PD placed their limbs more accurately after training in the U1°, U2°, B1°.
c) AM placed their limbs more accurately after training in the U1°, B1°.

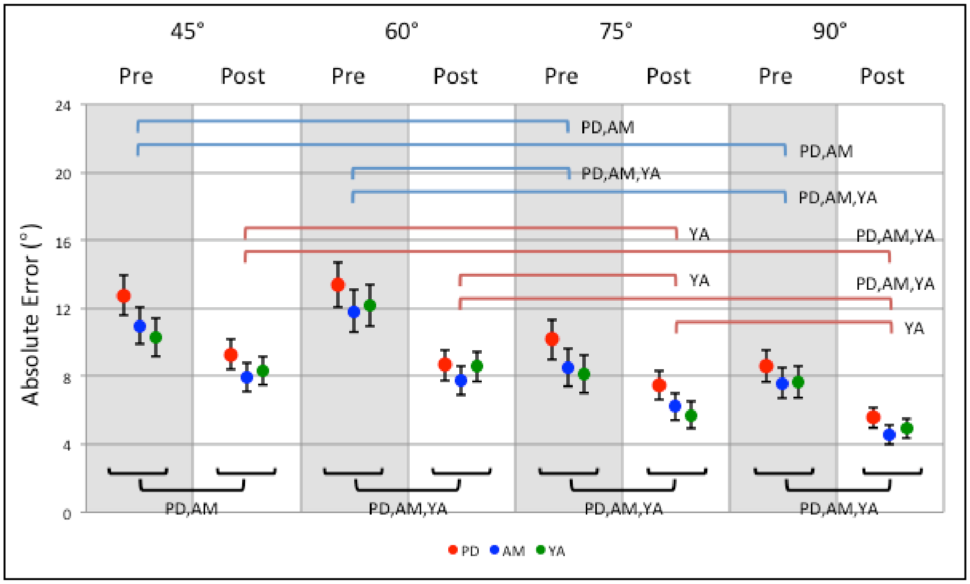


Figure 27. Accuracy of Limb Placement for Each Target, Pre- and Post- Training.
Placement Measure: E_{absN}. Comparison: Pre/Post−Target. Legend as described in Figure 25.
a) Most groups placed their limbs more accurately, for all targets, after training.
b) Many groups showed less accurate limb placement at lower targets.

5.2.2. Placement Measure Results, E_{absD}: Absolute Error for Delayed Feedback Trials

For each target, there were 4 training trials or TP with the following sequence of reaches: CDDDD, CDDDD, DDDDD, DDDDD. During the first training TP, the PD group placed their limbs less accurately than the AM and YA groups. During the last TP there were no observed differences between the groups. Each group was able to place their limbs more accurately during the last training TP than during the first. The accuracy of limb placement for each training TP can be seen in Figure 28.

When comparing accuracy across reaches, PD placed their limbs less accurately than AM and YA in the first TP, for reaches 3 and 5. Each group was able to place their limb more accurately at the end of TP 1; AM also improved in TP 3; PD also improved in TP 2 and 3. The accuracy of limb placement across reaches for each TP (1 to 4) can be seen in Figure 29.

When comparing accuracy for each side, for each TP, PD placed their limbs more accurately in the last training TP for the unilateral primary and both bilateral sides. The accuracy of limb placement for all sides for each TP can be seen in Figure 30.

When comparing accuracy for each target, for each TP, each group placed their limb less accurately at the 60° target than the 30° and 90° for first training TP. Each group placed their limbs more accurately at the 90° target than the 30° and 60° for the last training TP. For the 60° target, each group was more accurate during the last training TP. For the 90° target, PD was more accurate during the last training TP. The accuracy of limb placement for all targets for each TP can be seen in Figure 31.

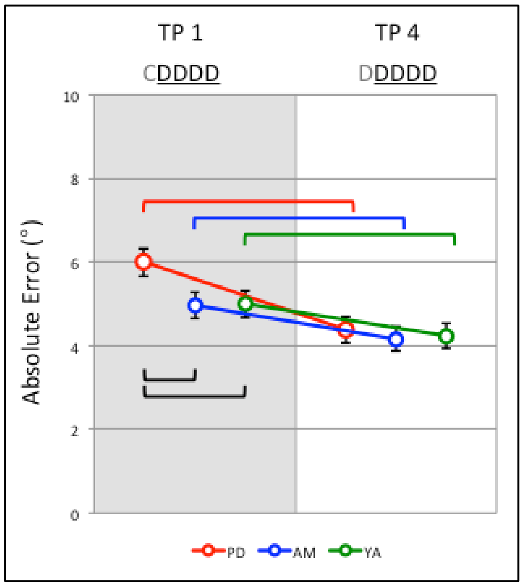


Figure 28. Accuracy of Limb Placement During First and Last Training Target Presentation. Placement Measures: E_{absD}. Comparison: TP (First/Last). Legend as described in Figure 25.
a) During the first training trial, PD was less accurate than the AM and YA group.
b) Each group placed their limbs more accurately during the last training trial.

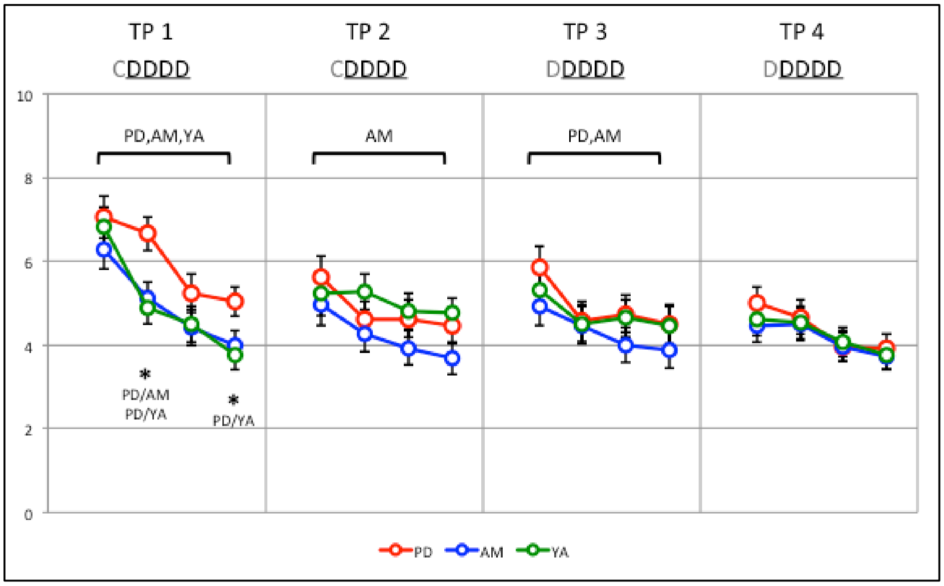


Figure 29. Accuracy of Limb Placement Across Reaches for Each Target Presentation. Placement Measures: E_{absD}. Comparison with Bonferroni Correction: TP-Reach. Legend as described in Figure 25.

a) PD was less accurate than AM and YA during training TP 1, reach 3 and 5.

b) Each group improved from reach 2 to 5 during training TP 1.

c) Some groups improved from reach 2 to 5 during training TP 2 and 3.

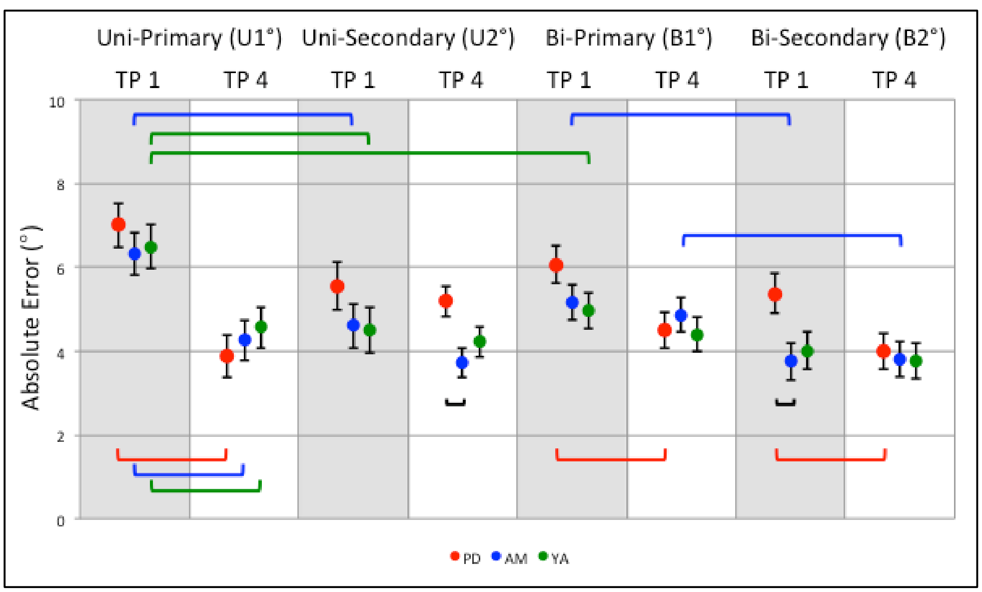


Figure 30. Accuracy of Limb Placement for All Sides, First and Last Target Presentation. Placement Measures: E_{absD}. Comparison with Bonferroni Correction: TP (First/Last)-Side. Legend as described in Figure 25.

a) PD placed their limbs more accurately in training TP 4 than in TP 1 for the U1°, B1°, B2°.

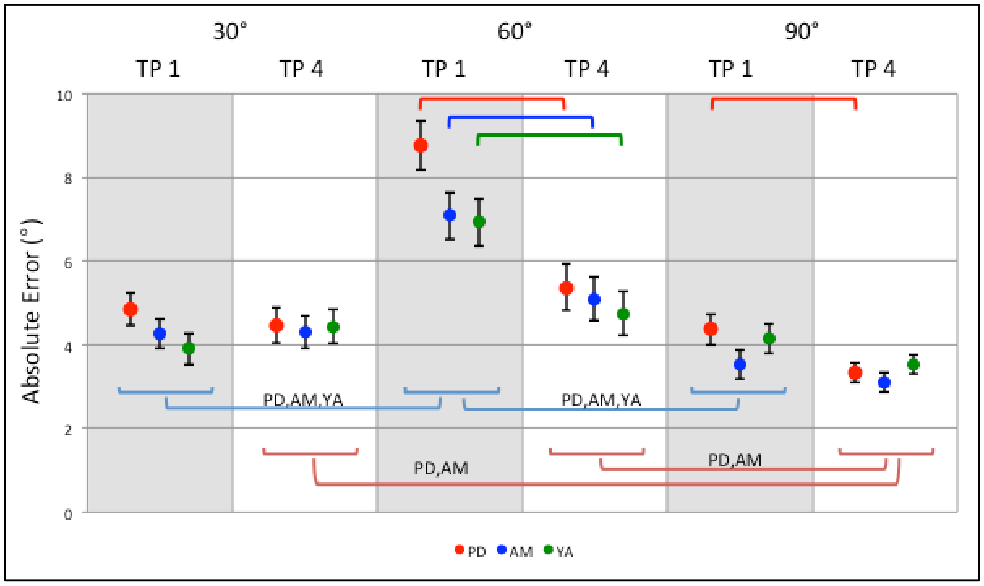


Figure 31. Accuracy of Limb Placement for All Targets, First and Last Target Presentation. Placement Measures: E_{absD}. Comparison with Bonferroni Correction: Trial (First/Last)-Target. Legend as described in Figure 25.
a) Each group placed their limb less accurately at the 60° than the 30 or 90° target for the first training trial.
b) PD and/or AM placed their limb more accurately at the 90° than the 30 or 60° target for the last training trial.
c) For 60° target, each group was more accurate during the last training trial.
d) For the 90° target, PD was more accurate during the last training trial.

5.2.3. Placement Measure Results, Sym_N: Symmetry

During the pre- and post- trials, there were no observed differences between the groups in the symmetry, which is the mean of the absolute maximum deviation between primary and secondary limb across reaches for bilateral trials. Overall, PD was more symmetrical after training and in particular, PD was more symmetrical at the 90° target after training. The symmetry of limb placement pre- and post- training can be seen in Figure 32 and the symmetry of limb placement for all target pre- and post- training can be seen in Figure 33.

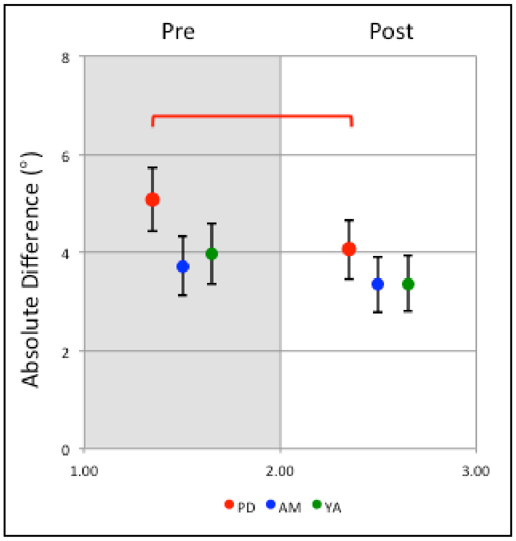


Figure 32. Symmetry of Limb Placement During Pre- and Post- Training.
Placement Measures: Sym_N. Comparison: Pre/Post. Legend as described in Figure 25.
a) PD was more symmetrical after training.

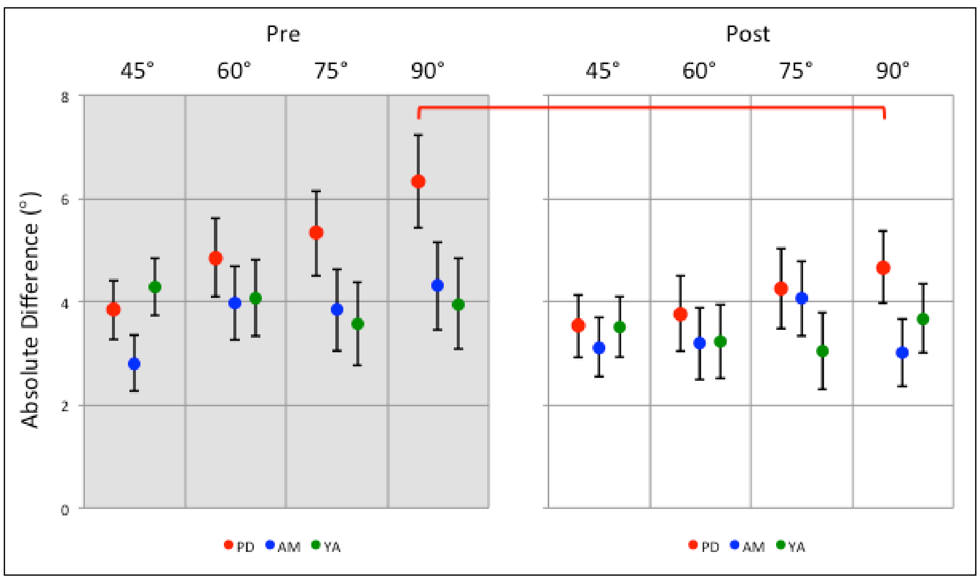


Figure 33. Symmetry of Limb Placement for All Targets, Pre- and Post- Training.
Placement Measures: Sym_N. Comparison with Bonferroni Correction: Pre/Post-Target. Legend as described in Figure 25.
a) PD was more symmetrical after training in the 90° target.

5.2.4. Placement Measure Results, V_{PeakN}: Velocity Peak

During the pre- and post- trials, each group moved with a higher velocity when moving to more distant targets. The peak velocity for each target, pre- and post-, can be seen in Figure 34.

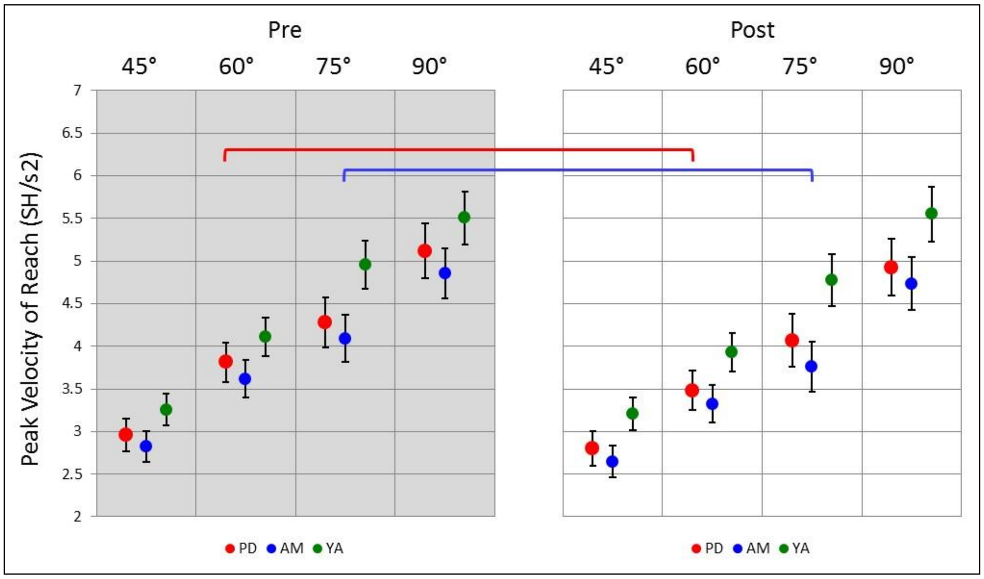


Figure 34. Peak Velocity of Limb Placement for All Targets, Pre- and Post- Training. Placement Measures: V_{PeakN}. Comparison with Bonferroni Correction: Pre/Post-Target. Legend as described in Figure 25.
a) Each group moved with higher velocity when moving to more distant targets.

5.2.5. Placement Measure Results, T_{EarlyN}: Early Movement Time

During the pre- and post- trials, young-able bodied had a shorter early movement time than the age-matched controls. There were no observed differences in the early movement time between the PD group and the control groups during pre- or post- trials.

5.2.6. Placement Measure Results, T_{MoveN}: Movement Time

During the pre- and post- trials, YA had a shorter movement time than AM. There were no observed differences in the movement time between the PD group and the control groups. PD had a shorter movement time after training than before training.

5.2.7. Placement Measure Results, $Range_N$: Range of No-Feedback Reaches

During the pre- and post- trials, several groups had higher ranges at lower targets, which can be seen in Figure 35.

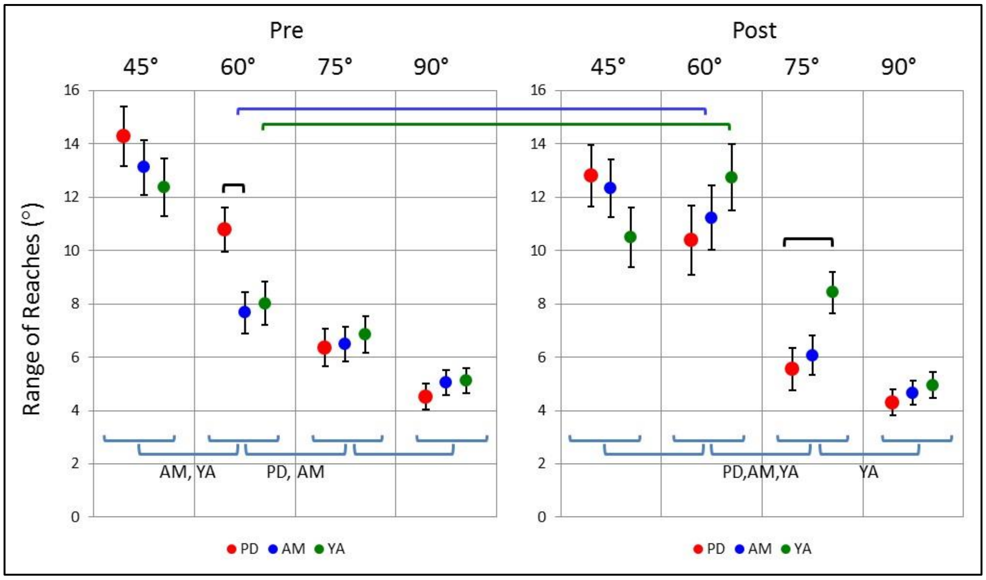


Figure 35. Range for No-Feedback Trials for All Targets, Pre- and Post- Training.
Placement Measures: V_{PeakN}. Comparison with Bonferroni Correction: Pre/Post-Target. Legend as described in Figure 25.
a) Several groups had higher ranges at lower targets.

CHAPTER 6

LIMB VELOCITY FEEDBACK RESULTS

During the limb velocity feedback protocol participants were asked to swing their arm up and down and match onscreen velocity targets. The trial order can be seen in Table 4.

6.1. Screened Participants Characteristics

The system was tested on 15 participants with Parkinson's disease (PD), 18 Age-Matched (AM) subjects and, 16 Young-Able Bodied (YA) participants.

Two age-matched subjects and one young able-bodied subject were excluded from the velocity analysis: participant AM_06 did not attempt the task, there was a protocol deviation on participant AM_13 (AM_13 was left-handed and tasks were accidentally performed with right-hand first) and participant YA_07 was unable to understand the task.

Information about the PD participants is shown in Table 7; AM participants in Table 8, and YA participants in Table 8.

6.2. Velocity Measurements

A detailed description of how the velocity measures were calculated can be seen in Section 4.4.2.

6.2.1. Velocity Measure Results, Acc: Accuracy

During the first and last velocity trial, with direct feedback, the PD and AM groups had lower accuracy than the YA group. PD also had higher accuracy during the last direct feedback training trial than the first training trial. The accuracy of limb velocity control for first and last TP is shown in Figure 36.

When comparing accuracy of velocity control for each side, PD was more accurate during the unilateral than the bilateral tasks during the direct feedback trials. For the direct bilateral primary limb, PD was less accurate than AM and YA; and AM was less accurate than YA. For the direct bilateral secondary limb, the PD and AM groups were less accurate than the YA group. The accuracy of limb velocity control for each side is shown in Figure 37.

When comparing accuracy of velocity control for each side, PD and AM were less accurate than YA during the direct feedback 80 and 110 target. Most groups were less accurate in the 80 than the 100A target. PD and AM were less accurate for several targets compared to the 100A target. The accuracy of limb velocity control for each target is shown in Figure 38.

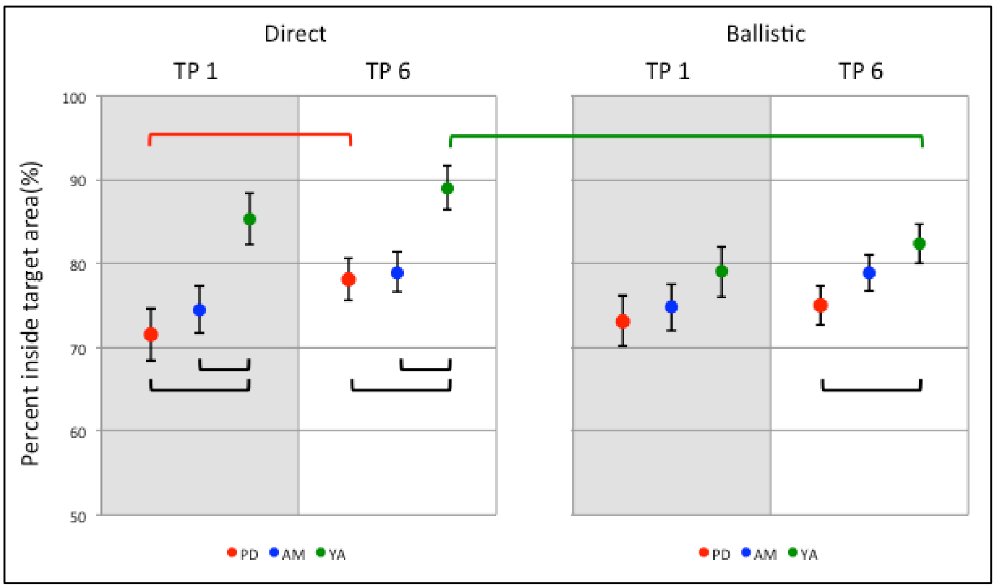


Figure 36. Accuracy of Limb Velocity for First and Last Target Presentation of Direct and Ballistic Feedback.
Velocity Measures: Acc. Comparison: First/Last TP. Legend as described in Figure 25.
a) PD and AM had a lower accuracy than YA for the direct feedback, first and last TP.
b) PD had a higher accuracy after direct feedback training than before

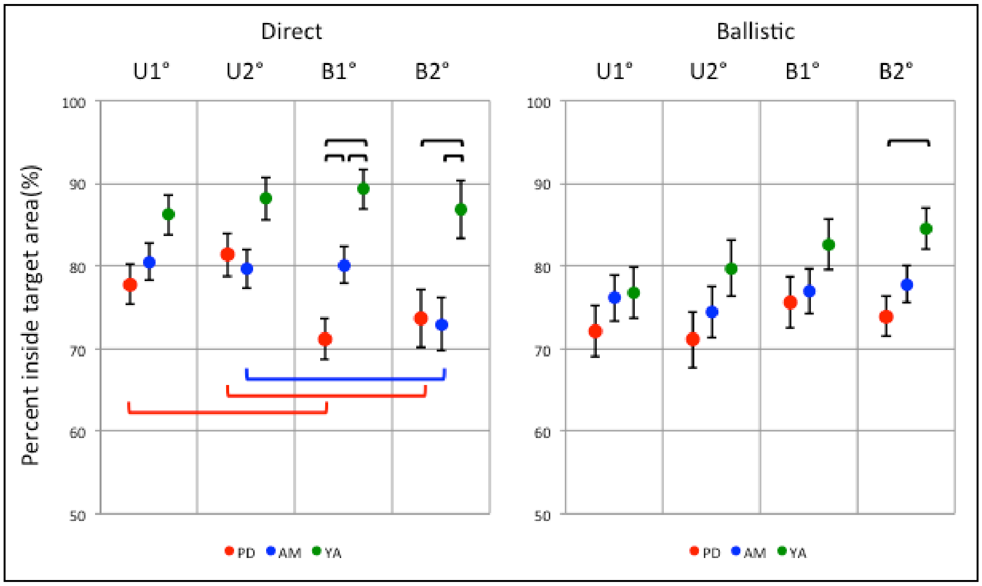


Figure 37. Accuracy of Limb Velocity for Each Side of Direct and Ballistic Feedback. Velocity Measures: Acc. Comparison: Side. Legend as described in Figure 25.
a) PD was less accurate than AM and YA during the direct bilateral primary limb.
b) AM was less accurate than YA in the direct bilateral primary limb.
c) PD and AM was less accurate than YA in the direct bilateral secondary limb.
d) PD performed better on unilateral than bilateral tasks in the direct feedback.

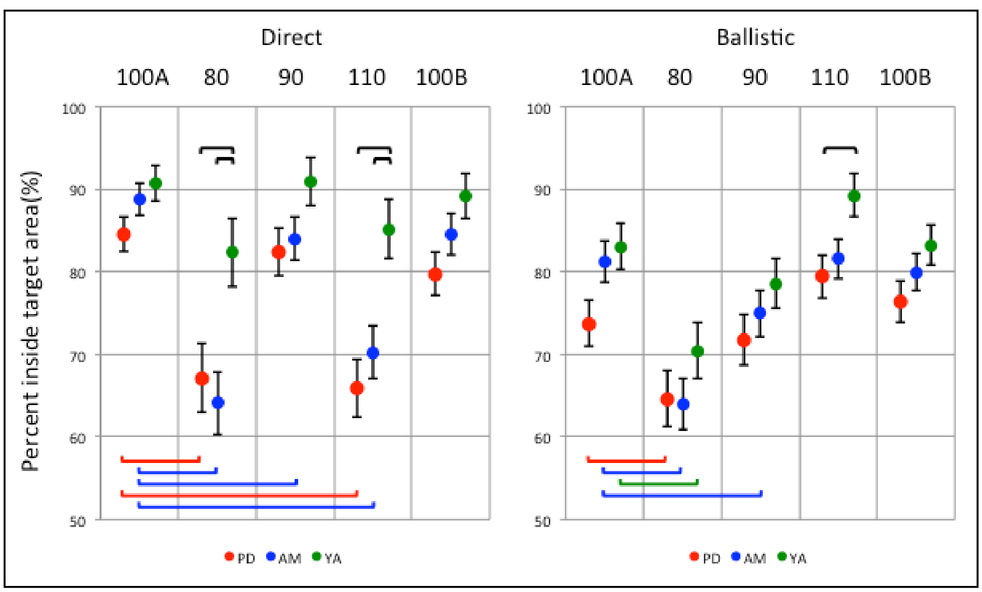


Figure 38. Accuracy of Limb Velocity for Each Target of Direct and Ballistic Feedback. Velocity Measures: Acc. Comparison: Target. Legend as described in Figure 25.
a) PD and AM was less accurate than YA during the direct 80 and 110 target.
b) Most groups were less accurate in the 80 compared to 100A.
c) PD and AM were less accurate in several targets compared to 100A.

6.2.2. Velocity Measure Results, Tot: Total

PD and YA had fewer swings per target during the ballistic feedback trials than during the direct feedback trials. When comparing total number of swings per target, most groups had more swings for the 90 and 110 targets than the 100A target for both the direct and ballistic feedback. The total number of swings per target for direct and ballistic feedback is shown in Figure 43 and the total number of swings per target for each target is shown in Figure 44.

6.2.3. Velocity Measure Results, Exc: Excursion

When comparing the excursion of each swing for each target, most groups had a higher excursion with higher velocity targets for both direct and ballistic feedback. The excursion for each swing for each target is shown in Figure 39.

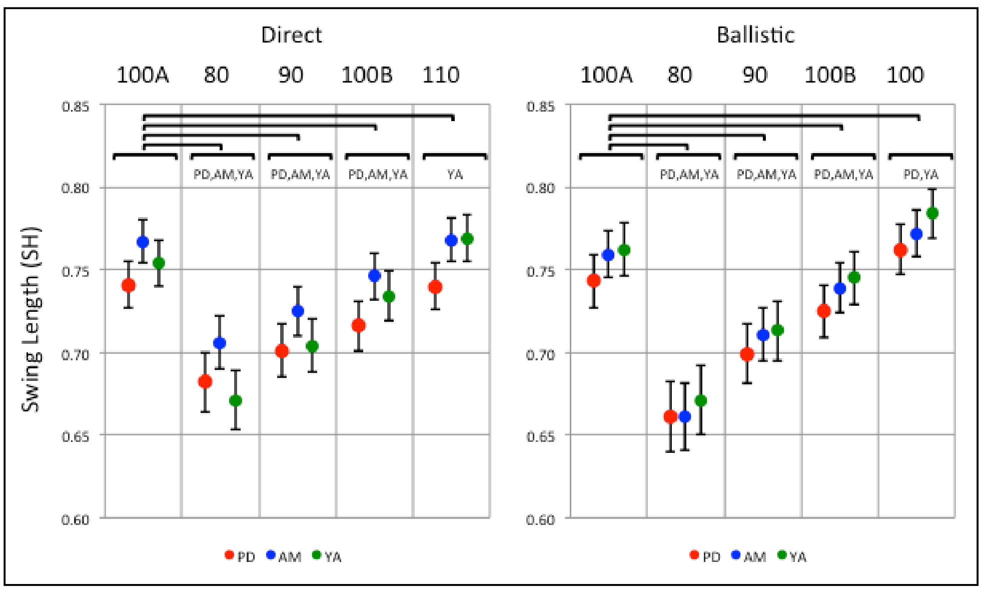


Figure 39. Excursion for Each Swing for Each Target of Direct and Ballistic Feedback. Velocity Measures: Exc. Comparison: Target. Legend as described in Figure 25.
a) Most groups had higher excursion with higher velocity targets.

6.2.4. Velocity Measure Results, Std_{aPeakX}: Standard Deviation of the Peak Position in the Lateral Direction

For the ballistic feedback, PD had a lower standard deviation of the peak lateral position of each target than AM. When comparing direct and ballistic feedback, AM and YA both had a higher standard deviation in the lateral peak position for ballistic compared to direct. The standard deviation of the lateral peak position of each target is shown in Figure 40.

When comparing the standard deviation of the lateral peak position of each target for each side, PD had a lower standard deviation than age-matched for several sides in the direct and ballistic feedback. When comparing the standard deviation of the lateral peak position of each target for each target, PD had a lower standard deviation than age-matched for all ballistic targets. The standard deviation of the lateral peak position of each target for each side and for each target is shown in Figures 45 and 46, respectively.

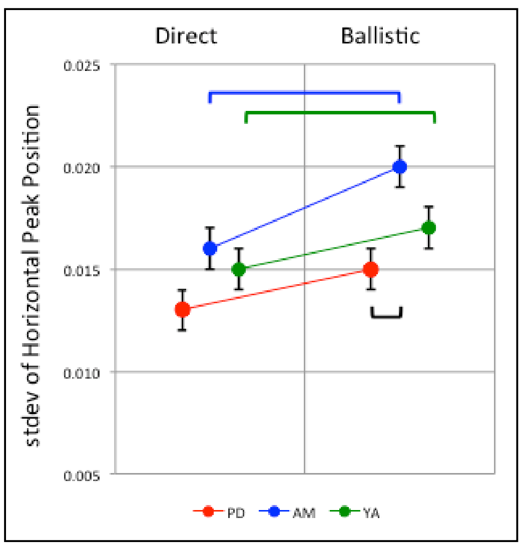


Figure 40. Standard Deviation of the Lateral Peak Position for the Direct and Ballistic Feedback. Velocity Measures: Std_{aPeakX}. Comparison: Feedback. Legend as described in Figure 25.
a) For ballistic (compared to direct), AM and YA showed a higher standard deviation in the lateral peak position.
b) PD showed a lower standard deviation than AM in the ballistic feedback

6.2.5. Velocity Measure Results, Std_{aPeakY}: Standard Deviation of the Peak Position in the Vertical Direction

Each group had a higher standard deviation of the peak vertical position of each target for the ballistic feedback compared to the direct feedback. When comparing the standard deviation of the peak vertical position of each target for each target, each group had higher standard deviation for the 80 target compared to the 100A target. The standard deviation of the vertical peak position of each target for ballistic and direct feedback and for each target is shown in Figure 47 and 48, respectively.

6.2.6. Velocity Measure Results, Recip: Reciprocity

Each group had a higher reciprocity for the direct feedback compared to the ballistic feedback. For the direct feedback, PD and AM were more reciprocal during the last trial compared to the first trial and PD and AM were more reciprocal during the 110 target compared to the 100A target. For the ballistic feedback, YA was more reciprocal during the last trial compared to the first trial and YA was more reciprocal during the 110 target compared to the 100A target. The reciprocity of each target for direct and ballistic feedback, for the first and list trial, and for each target is shown in Figures, 41, 42, and 49, respectively.

6.2.7. Velocity Measure Results, Sym: Symmetry

For the direct or ballistic feedback, there was no statistical difference between the symmetrical timing of each group. For the direct feedback, YA was more symmetrical at the 90 target than the 100A target and AM was more symmetrical at the 110 target than the 100A target. The symmetrical timing of each target for direct and ballistic feedback and for each target is shown in Figures 50 and 51, respectively.

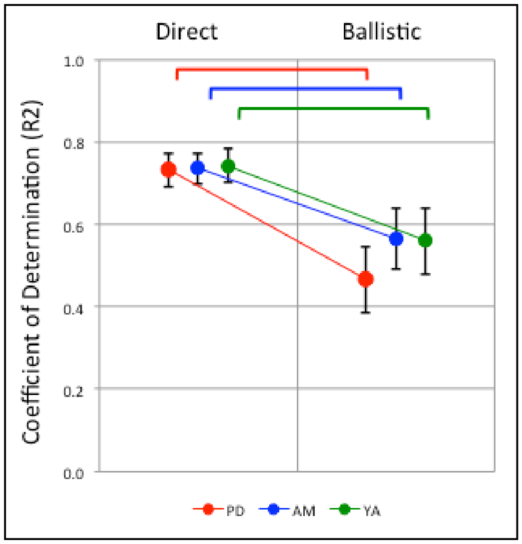


Figure 41. Reciprocity of Each Target for Direct and Ballistic Feedback.
Velocity Measures: Recip. Comparison: Feedback. Legend as described in Figure 25.
a) Each group was less reciprocal in the ballistic feedback.

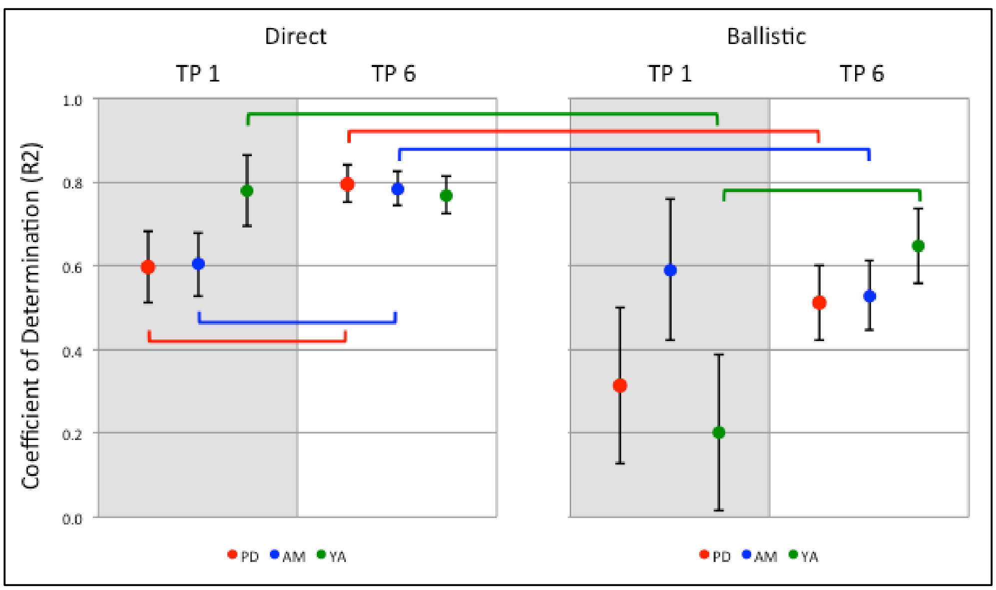


Figure 42. Reciprocity of Each Target for the First and Last Target Presentation of Direct and Ballistic Feedback.
Velocity Measures: Recip. Comparison: TP (First/Last). Legend as described in Figure 25.
a) PD and AM were more reciprocal in Direct Trial 6.
b) YA was more reciprocal in Ballistic Trial 6.

6.2.8. Velocity Measure Results, Dev_{Mid}: Mean of the Midpoint Lateral Deviation of Each Swing

For the first trial of direct feedback, AM had a higher midpoint lateral deviation than YA For the first and last trial of ballistic feedback, AM had a higher midpoint lateral deviation than YA. The mean of midpoint of the lateral deviation for the first and last trial of direct and ballistic feedback can be found in Figure 52.

6.2.9. Velocity Measure Results, Dev_{HL}: Mean of the Peak-Valley Lateral Deviation of Each Swing

For the direct feedback, AM had a higher peak-valley lateral deviation than YA for the unilateral secondary side (U2°) and PD had a higher peak-valley lateral deviation than AM for the secondary primary side (B1°).

6.2.10. Velocity Measure Results, $Hull_{Area}$: Hull Area

For the direct feedback, PD had a lower hull area than AM for the unilateral and bilateral secondary side (U2° and B2°). For the ballistic feedback, PD had a lower hull area than AM for the unilateral and bilateral secondary side (U2° and B2°) and PD had a lower hull area than YA for the unilateral secondary side (U2°).

6.2.11. Velocity Measure Results, $Hull_{Width}$: Hull Width

For the direct feedback, PD had a lower hull width than AM for the unilateral and bilateral secondary side (U2° and B2°). For the ballistic feedback, PD had a lower hull width than AM and YA for the unilateral and bilateral secondary side (U2° and B2°).

CHAPTER 7

DISCUSSION

7.1. Summary of Results

7.1.1. Limb Placement Results

The following is a summary of the results extracted from Chapter 5, Limb Placement Feedback Results.

All groups:

- Each group was able to perform the task.
- Each group placed their limb more accurately after training (E_{absN}, E_{absD}).
- Each group showed improvement on the unilateral primary limb (E_{absN}, E_{absD}).
- Most groups showed less accuracy at lower targets (E_{absN}).
- The 60° target was the hardest target (E_{absD}).
- The 90° target was the easiest target (E_{absD}).
- Each group moved with higher velocities to further targets (V_{PeakN}).
- Several groups exhibited a higher range of movement amplitudes at lower targets.

For the PD group:

- During the first training trial, PD placed their limb less accurately than AM and YA (E_{absD}).
- During the last training trial, PD placed their limb as accurately as AM and YA (E_{absD}).
- PD showed improvement across several sides: Pre/Post (U1°, B1°) and Training (B1°, B2°).
- PD placed their limbs to the 90° target more accurately after training (E_{absD}).
- PD was more symmetrical after training (Sym_N).

7.1.2. Limb Velocity Results

The following is a summary of the results extracted from Chapter 6, Limb Velocity Feedback Results.

All groups:

- Each group was able to perform the tasks.
- There was a greater distinction in accuracy between groups in the direct feedback (Acc).
- Most groups had a higher excursion with higher velocity targets (Exc).
- Most groups had less swings per target during direct feedback (Tot).
- Most groups had a higher lateral and vertical peak position standard deviation during ballistic feedback (Std_{aPeakx}, Std_{aPeaky}).
- Each group was less reciprocal during ballistic feedback (Recip).

Age-Matched and Parkinson's versus Young Able-Bodied

- PD and AM had a lower accuracy than YA in the direct feedback (Acc).
- For the direct bilateral secondary limb, PD and AM were less accurate than YA (Acc).
- For the direct 80 and 110 target, PD and AM were less accurate than YA (Acc).

Parkinson's:

- PD performed better on unilateral than bilateral tasks in the direct feedback (Acc).
- PD had a higher accuracy after direct feedback training (Acc)
- For the direct bilateral primary limb, PD was less accurate than AM and YA (Acc).
- For the direct bilateral primary limb, AM was less accurate than YA (Acc).
- PD (and AM) were more reciprocal after direct feedback training (Recip).
- For several sides and targets, PD had a lower lateral peak position standard deviation than AM (std_{aPeakx}).

7.2. Interpretation

7.2.1. Effects of Impaired Somatosensation Ameliorated With Visual Biofeedback

The motor symptoms of PD are caused by the degeneration of the dopaminergic nigrostriatal pathway resulting in an over-excitation of the output pathways of the basal ganglia to the thalamus, which integrates this information from the basal ganglia with multiple modalities of sensory information. In this research, we displayed visual information that provided the participant with an indication of limb placement error that occurred during the phase of movement that relied on somatosensory input. The integration of visual, somatosensory and motor signals from basal ganglia resulted in changes in sensorimotor processing (presumably in the thalamus) to improve limb placement capabilities.

It has been suggested that hypokinetic movement in people with PD may result from impaired somatosensation (Pessiglione 2005; Konczak 2007). Studies have shown that people with PD have an impaired ability to identify small externally imposed movement in the finger, wrist, elbow and shoulder (finger, wrist, shoulder: Schneider 1987; elbow: Koczak 2007; Zia 2000), an impaired ability to identify which elbow is more flexed or extended (O'Suilleabhain 2001; Zia 2000), and an impaired ability to perform contralateral elbow matching (O'Suilleabhain 2001). During voluntary directed movement, it is believed the brain utilizes an internal model of the body and the external environment that has been iteratively learned through experience (Shadmehr 2010). The internal model is used to produce motor commands that will result in the desired movement. The depletion of dopamine in the basal ganglia in PD may corrupt the internal model, which would result in impaired movements. Studies have shown that people with PD have trouble pointing to an external target when vision is occluded (Adamovich 2001; Klockgether 1994) thus demonstrating the impairment of the internal model. However, the same participants did not demonstrate difficultly when vision was not occluded, which suggests that the visual information can be used to correct for errors in the internal model.

Visual cueing, such as lines or markers on the floor, has been shown to increase stride length, improve stride length regulation, and increase gait velocity in people with PD (Lim 2005; Lewis 2000; Azulay 1999; Azulay 2006). Although the exact cause of the marked change is not known, it has been suggested that visual cues may either trigger a step, draw attention to the stepping process, provide dynamic visual feedback (Azulay 2006; Azulay 1999) or some combination of the above. The carry-over effects from visual cueing suggest that visual feedback may alter perception of movement derived from somatosensory inputs and/or the process of sensorimotor integration.

In the Limb Placement Feedback training task, participants were asked to reach to targets without feedback (similar to the occluded vision condition in other studies) and then adjust with feedback. As with Adamovich (2001) and Klockgether (1994), participants with PD had trouble reaching to targets when vision was occluded (see Figure 28 and 29). However, after training and corrective feedback, participants were able to reach to targets as well as age-matched and young-able bodied controls. Much like the dynamic feedback in over ground walking (Azulay 2006), the corrective feedback allowed participants to see and correct the error in reach before making another reach. The corrective feedback also drew the participant's attention to the error and the error correction (Azulay 2006). The carry-over effect from this (and from the visual cueing) suggest that visual feedback and error correction may help people with PD alter their perception of movement, sense their error and adapt.

Some of the initial symptoms of PD are unilateral, generally a reduction in arm swing during gait or resting tremor in a single limb (Mayeux 2003); this symptom is often not evident to the person with PD but it is often a spouse who first notices the symptoms. During the bilateral task, not only were participants able to see the error in their reach, they were able to see any lack of bilateral symmetry in their reach. Although the differences were not statistically significant, participants with PD trended toward less symmetry for the more distant targets. Participants with PD were able to see if one hand was higher or lower than the other hand. At times, possibly in anticipation of a placement error, participants with PD over-compensated and placed the most affected hand higher than the last affected hand. After training, participants with PD were more symmetrical in their reaches, particularly at the 90° target (see Figure 32 and 33). The bilateral 90° target, i.e. the "T-pose" where the arms are straight out to the side, is the most recognizable of the targets and may be the target that can best utilize the participant's internal model.

This system, which provides corrective feedback to allow a participant to see and correct their error, can be seen as a way to alter the internal model. In subsequent reaches, after seeing and correcting their error, participants adjust their internal model to compensate for their general reduction in movement to reach the target.

7.2.1.1. Limitations. In this study, we demonstrated that participants were able to use feedback to improve limb placement and limb velocity control, but some factors may limit the generalizability of our results. During the study, participants were asked to wear comfortable clothing and their clothing was not modified to avoid cutaneous stimulation on the arm during arm movements. It is possible, that some subjects may have used cutaneous signal produced by their clothing to improve their limb placement accuracy. However, given the active nature of the task and the fact that the arm movements involved at most 90° of rotation at the shoulder, we believe it is unlikely this cutaneous input substantially affected the results of the study.

A second factor that may have influenced the results is the nature of the target that was presented to the participant during the limb placement task. The circular target was large and therefore a large range of shoulder angles could be used to place the limb in the target. The tolerance for each target was ±6.85-8.83°; the tolerance for a given subject depended on the scaling that was used to ensure that projected height of the subject on the screen was the same for all participants. It is possible that use of a smaller target would have encouraged more accurate placement and promoted more pronounced motor learning. However, a target that is too small could generate frustration in a group with movement disabilities. We believe the target size used in the study provided a sufficient challenge to exhibit errors and induce learning. In this study, participants were asked to reach to the center of the target, however, the target changed if participants were in the target area, regardless of whether the participant was in the center. Placing a smaller circle at the center of the target area may have encouraged participants to aim for the center of the target and may have resulted in more pronounced improvements in placement accuracy.

7.2.2. Encouraging High Velocity Movements

Although the primary treatment for PD is dopamine therapy, there is a growing interest in the use of exercise and physical therapy to ameliorate symptoms and/or slow disease progression. In one study, large amplitude and high velocity exercises have been shown to increase amplitude and velocity in participants with PD (Farley 2005). In these studies, participants were asked to think “BIG” while moving. It is believed that the intrinsic cueing encouraged participants to move bigger. In a study by Majsak et al. (1998), participants moved faster to fast-moving targets than to stationary targets when asked to move “As Fast As Possible”. This study provides an example of how extrinsic cueing can be used to affect limb velocity.

In the Limb Velocity Feedback task, we mimicked some of the movements in the BIG paradigm except that we used extrinsic cueing and we used a range of target velocities that included values that were slower as well as faster than their “As Fast As Comfortable” velocity. In our study, participants were asked to modulate their speed to 80, 90, 100, and 110% of their “As Fast As Comfortable” (AFAC) speed. Their ability to hit the 110% AFAC target (see Figure 38) extends the work of Majsak et al. (1998) because it not only provides another example of how extrinsic cueing can be used to increase limb movement velocity, but it demonstrates that people with PD are able to increase velocity in response to external cues and that they are able to increase velocity accurately. Furthermore, the results for the slower target values (80%, 90%) demonstrate that people with PD can accurately and reliably produce arm movements that are slower than AFAC, but their consistency was lower for the slower movements.

With direct feedback, in the initial trials (see Figure 36), participants with PD were able to hit and modulate their speed to hit the targets as accurately as the age-matched control subjects. However, both of the older groups (participants with PD and age-matched control subjects) were less accurate than the young-able bodied control subjects. Participants with PD, over the course of training, were able to use the visual feedback to modulate their speed more accurately.

With ballistic feedback, participants with PD were able to hit the 110% AFAC target as accurately as the 100% AFAC target (see Figure 38). With both types of velocity feedback, direct and ballistic, the participant were not informed that the 110% target was faster than their AFAC speed; participants just interacted or played the game.

These results demonstrate that extrinsic cueing of velocity can be an effective way to encourage people with PD to modulate their movement velocity. The participants were able to interpret the visual feedback and act on it appropriately. Importantly, they were able to increase their movement speed in a consistent manner.

7.2.3. Amplitude and Velocity Co-Vary

During the limb placement feedback task, each group moved faster when asked to move to further targets (see Figure 34); during the limb velocity feedback task, each group increased their swing excursions (or amplitude) to reach the higher velocity targets (see Figure 39). For both the limb placement and limb velocity feedback task, there was a clear correlation between the amplitude and velocity. This correlation between amplitude and velocity was evident in all groups. Participants with PD were able to co-vary their amplitude and velocity in a manner that was very similar to the control groups. This suggests that the structures and pathways utilized to modulate these tasks may not be impaired.

7.3. Implications

7.3.1. Feedback Allows Participants to See and Correct Their Error

This research has demonstrated that people with PD were able to use corrective feedback to improve limb placement and limb velocity. In particular, visual feedback and corrective feedback allowed participants to see their error in real-time and to correct for it in a manner that induced a training effect. That is, in subsequent trials, their limb placement was more accurate in the phase of the movement before feedback was delivered. The learning that occurred in participants with PD allowed them to reach a level of performance by the end of the session that was indistinguishable from that of age-matched and young able-bodied controls. These results support the use of therapeutic paradigms that visual feedback to improve limb placement capability of people with PD.

7.3.1.1. Target Location. The easiest target was the 90° (or the “T-pose”), see Figure 27, which may be the target that can best utilize the participant’s internal model; the hardest target was the 60° which was somewhere between the middle (45°) and straight out to the side (90°). It is likely, this target 60° was the hardest as it is not in a standard location. When designing future systems, it may be good to vary the target location to increase or decrease difficulty.

7.3.2. Feedback Can Be Used to Encourage Large Amplitude and High Velocity Movement

In previous work, visual cueing has been shown to increase stride length and stride length regulation by proving dynamic feedback and drawing attention to the stepping process. In addition, large amplitude and high velocity exercises have been shown to increase amplitude and velocity of movement. If combined with visual feedback and corrective feedback, large amplitude and high velocity of movement can be used to allow participants to see their amplitude and velocity of movement, to encourage larger amplitude and velocity of movement, and to track progression of amplitude and velocity of movement. These types of therapeutic protocols may have benefits that match, or even exceed, those obtained from the use of BIG movement therapy.

7.3.2.1. Type of Feedback. Although while using the system, participants reported the ballistic system was more entertaining, as it mimicked a very natural system, the velocity feedback of the system was delayed. The instantaneous velocity of the upward arm swing was mapped to the output velocity of the fountain. As a result, there was delay between when the maximum velocity of the arm swing occurred and the time that the fountain reached its peak height.

During direct feedback, participants received immediate feedback on whether their instantaneous velocity matched the target speed. In the direct feedback system, the instantaneous velocity was mapped directly to the width of the swinging bar that is used to match the onscreen target speed. The onscreen target flashes when the participant hits the target speed and flashes red when the subject exceeds the target speed. Possibly as a result of this immediate feedback, the difference in accuracy between the various groups was more pronounced. In addition, reciprocity (one arm swings up as the other arm swings down) was greater for the direct feedback. This may be a result of the high degree of attention that was required of the participants during the direct feedback trials.

7.3.3. Potential for Integration Into Commercially-Available Game Systems

Currently, there are many game systems on the market that that monitor limb movement or track whole body movement. The systems that have been developed in this work can be implemented on the commercially-available game systems to allow people with PD to perform these exercises at home and to allow their neurologist/physical therapist to track their progress. Not only has daily exercise has been shown to improve motor performance in people with PD (Calgar 2005), such an implementation would allow the clinician or the game to increase difficulty to encourage more accurate limb placement or larger and/or faster movements.

In future development of a game system, it will be important to test the type of exercise and the type of feedback. In our work, we looked at the symptoms of PD and generated our system based on that impairment. When performing the same exercise with different types of feedback (direct and ballistic as in the Limb Velocity System), participants exhibited differences in performance. Based on goals of the system, the feedback and exercise should be adapted accordingly. It would not be appropriate to take an off-the-shelf game system and assume it will be beneficial for rehabilitation. Although there are many games currently on the market, their benefits or detriments to performance in a group with a disability should be documented. It is possible that the exercise mode or the type feedback may participants to adopt an awkward position or movement pattern. In testing the ballistic feedback in the Limb Velocity System, we noticed that in their initial swings some participants waited for the fountain to reach its peak before continuing with the swinging motion. They quickly adjusted their pattern to produce a continuous reciprocal swinging motion, but it does demonstrate that the type of feedback can affect the participant’s ability to perform the task as intended.

7.4. Future Work

Although, we were able to demonstrate that people with PD were able to adjust their reach and swing velocity to reach onscreen targets, there is a large amount of work that should be done to help understand the effects of PD and to develop new forms of therapy.

There are three main research paths that can be pursued: 1) further investigations into sensorimotor function and sensorimotor learning capacity in people with PD can be performed, 2) the system can be enhanced to enable use in sensorimotor therapy, and 3) the system can be developed into a home-based system.

7.4.1. Characterizing Sensorimotor Function and Sensorimotor Learning in People With PD

In this research, we focused on using visual feedback to determine if people with PD have an impaired ability to control limb placement and if people with PD have an impaired ability to control limb velocity. This research focused on movement in the vertical direction of the coronal place and the vertical direction of the sagittal plane. The general concepts of this research could be expanded in several directions.

7.4.1.1. Learning and Translation to Improve Activities of Daily Living. In this research, participants performed a single task (reaching or swinging) over the course of a session. The protocol was designed to be repetitive to determine the short-term learning effect. Future research could focus on determining the best learning protocol for long-term retention or, since Parkinson's is a degenerative disease, long-term reduction of PD symptoms. The next stage of this research should include a longitudinal study to determine the carry-over affects into the activities of daily living.

7.4.1.2. Other Types of Movements. In the current research, we performed reaching in the vertical direction of the coronal plane and arm swinging in the vertical direction of the sagittal plane. This research could be expanded to include other types of movement. This research could be expanded to reaches or swings in the vertical, lateral, and longitudinal direction of the coronal, sagittal, and transverse plane.

In early iterations of the system, we included additional exercises from the BIG protocol (Farley 2005), we included side-to-side reaching in the horizontal direction of the coronal plane and side-to-side swinging in the transverse plane. However, we did not include these movements in this initial set of studies. Given the success of the feedback for movements in the vertical direction, attempts should be made to explore the other axes of movement.

A major aspect of the BIG protocol (Farley 2005) is the whole body movement. By using multiple targets, this research could be expanded to encourage multiple limb movement (arm/arm or arm/leg). In an early iteration of the system development, we used silhouette matching to encourage participants to stretch, lean, and bend their knee to match the onscreen silhouette. In another iteration, we used targets for placement of the feet that is similar to those presented for the hand. These strategies could be revisited and considered for use in future investigations.

7.4.1.3. Best Form of Feedback. In this research, we focused on using two different types of feedback to allow participants to see and correct their error in limb placement and limb velocity. In the limb placement task we used stationary targets and no-feedback/feedback conditions of the location of the hand to encourage accurate limb placement; in the limb velocity task we used stationary velocity targets with real-time feedback of the instantaneous movement velocity of the hand to encourage velocity control. In both the limb placement and limb velocity task, we used stationary targets that changed infrequently and were mapped to a single movement characteristic (position or velocity).

Future studies could explore the usage of moving targets, multiple targets, smaller targets, or targets that change with each successful or successive action. These studies could explore mapping the feedback to multiple movement characteristics. For example, the retroreflective wand could be mapped to a basketball and participants could be asked to throw the ball at onscreen targets; this mapping would require information on both the location and velocity of the hand.

In this research we focused on the effects of visual cues and visual feedback, other studies have shown that other forms of cues and feedback, such as auditory (Lim 2005) have been successful at helping people with PD increase and regulate walking speed. This research could be expanded to include music to see if it could be used to help regulate timing symmetry, reciprocity, or limb velocity.

7.4.1.4. Other Movement Disorders. This research focused on rehabilitation for people with PD. It is possible that this research can be expanded to other movement disorders. The systems, as is, were designed to be simple and flexible. The system was designed for people with PD, it was designed to target the reduced amplitude and velocity of movement by helping participants to see the deficits in their movement patterns and to make adjustments. The system could be used for Huntington's disease; the main symptom of Huntington's disease is the increase movement due to increased levels of dopamine. A similar type of system could be used to encourage people with Huntington's disease to hold or control their movement.

The system was designed to be simple, low-cost and versatile. As is, the limb placement feedback system, could be used by a participant sitting down. Also with no modification, the system could be adjusted to increase or decrease the hold time.

7.4.2. Therapeutic Diagnostics

One of the original intentions in developing the system was the use of minimal and simple hardware thus making it easy to be utilized in a physical therapy clinic. In the clinic, it could be used for physical therapy, to characterize the deficits, and/or as a biomarker to track disease progression.

7.4.3. In the Home

7.4.3.1. Engagement. Although the feedback systems were successful at showing improvement in people with PD, it was not very successful in keeping participants engaged. The systems and protocol were designed to encourage learning over a short period of time, which unfortunately resulted in a lot of repetition. In future designs of the system, especially with regard to a home-based system, gaming theory and engagement should be taken into consideration. In order for the system to be useful in the long-term, participants are going to have to want to play the game.

To make the system more engaging, different forms of feedback could be used and faster movements could be encouraged. During the limb velocity system the movements and feedback were faster than during the Limb Placement System, as a result participants were more engaged and more motivated to perform better.

7.4.3.2. Scoring/Increasing Levels of Difficulty. One of the advantages of a home-based system would be that it could enable continual usage by the participants. By performing therapy daily, participants would have less risk of regressing between therapy sessions. As stated in the previous section, for the system to be used regularly, the system would have to be engaging. One method of engagement could be scoring and/or increasing levels of difficulty. This would have several advantages. Scoring would allow the participant to see how they are doing during the current session, to see whether they are getting better from trial-to-trial or session-to-session, it would also allow participants to try to compete with their previous scores and encourage them to do better. Increasing levels of difficulty would allow participants to be continually challenged and to improve over time.

7.4.3.3. Long-Term Tracking. As stated in the previous section, a home-based system could be used daily. As a result, this data could be saved and transmitted to physical therapist for long-term tracking of the disease progression. This data could be transmitted via a secured pathway given that most game systems currently on the market have built-in internet connection.

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APPENDIX A

CHARACTERISTICS OF MOVEMENT DURING LIMB VELOCITY FEEDBACK TRIALS

The main text of the dissertation briefly summarizes the results of analysis that characterized the movements during the Limb Velocity trials. The data are presented in this Appendix.

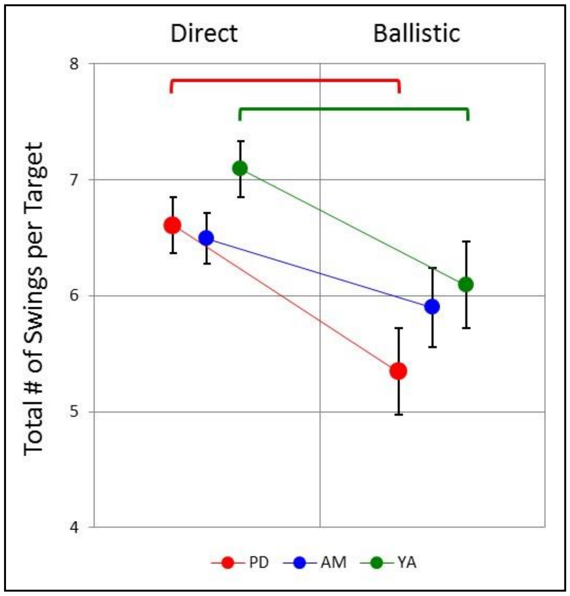

Figure 43. Total Number of Swings per Target for Direct and Ballistic Feedback.
Velocity Measures: Tot. Comparison: Feedback. Legend as described in Figure 25.
a) PD and YA had less swings per target during the ballistic feedback trials compared to the directed feedback trials.

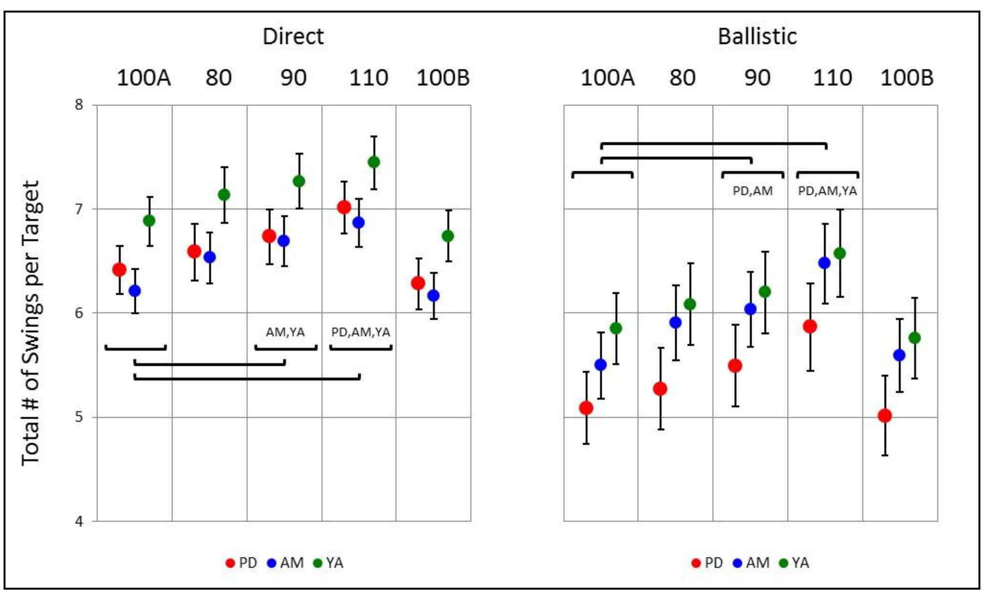

Figure 44. Total Number of Swings per Target for Each Target for Direct and Ballistic Feedback.
Velocity Measures: Tot. Comparison: Target. Legend as described in Figure 25.
a) Most groups had a greater number of swings during the 90 and 110 target than the 100A target.

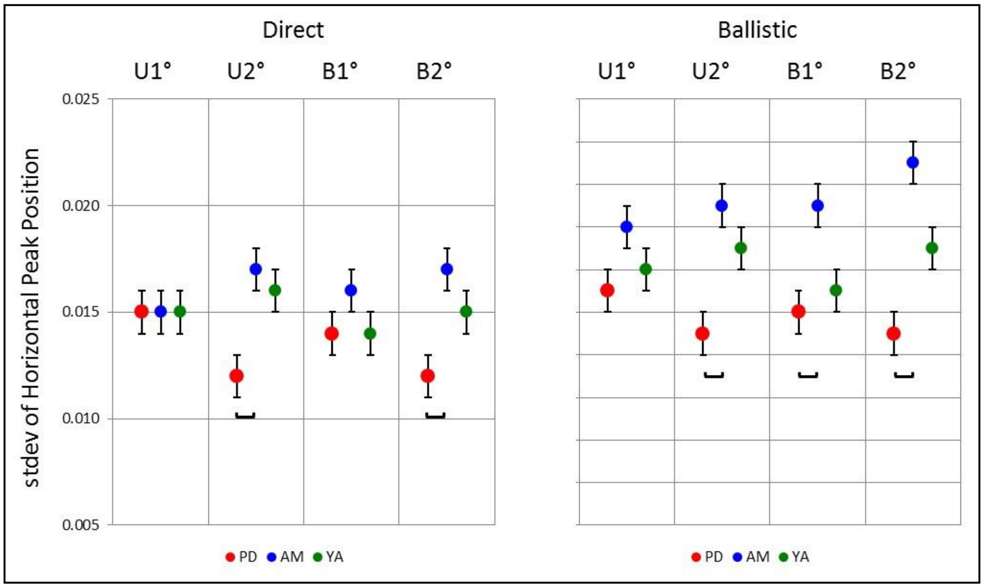

Figure 45. Standard Deviation of the Lateral Peak Position for Each Side for Direct and Ballistic Feedback.
Velocity Measures: Std_{aPeakX}. Comparison: Side. Legend as described in Figure 25.
a) For several sides in the direct and ballistic feedback, PD had a lower standard deviation in the lateral peak position than AM.

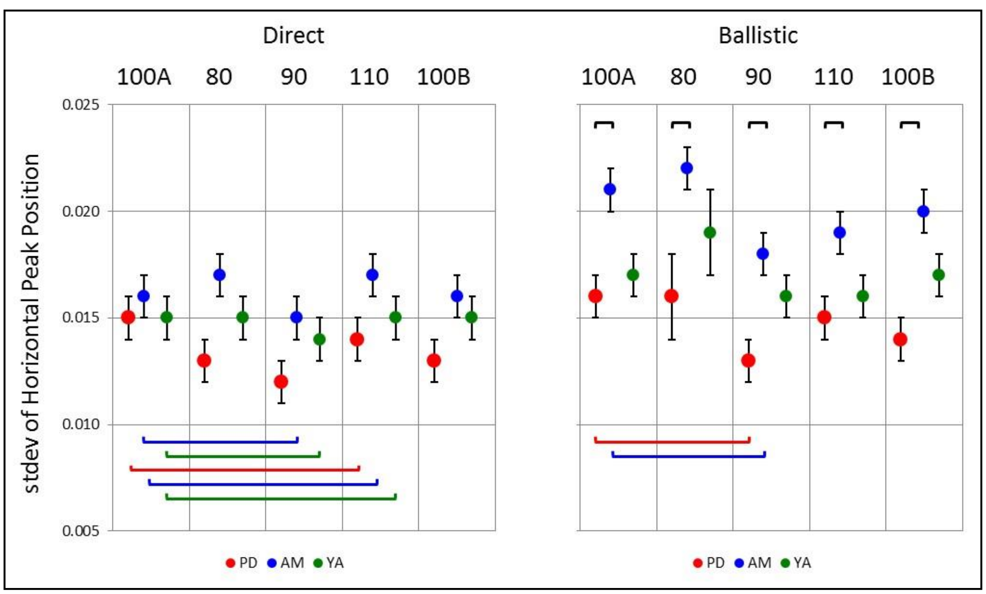

Figure 46. Standard Deviation of the Lateral Peak Position for Each Target for Direct and Ballistic Feedback.
Velocity Measures: Std_{aPeakX}. Comparison: Target. Legend as described in Figure 25.
a) For all ballistic targets, PD had a lower standard deviation in the lateral peak position than AM.

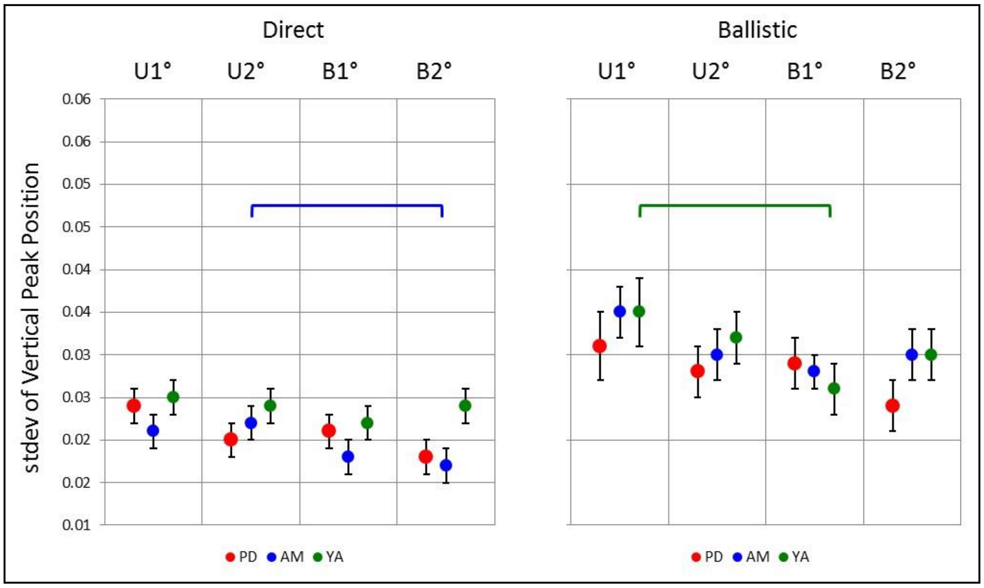

Figure 47. Standard Deviation of the Vertical Peak Position for Each Side for Direct and Ballistic Feedback.
Velocity Measures: Std_{aPeakY}. Comparison: Side. Legend as described in Figure 25.

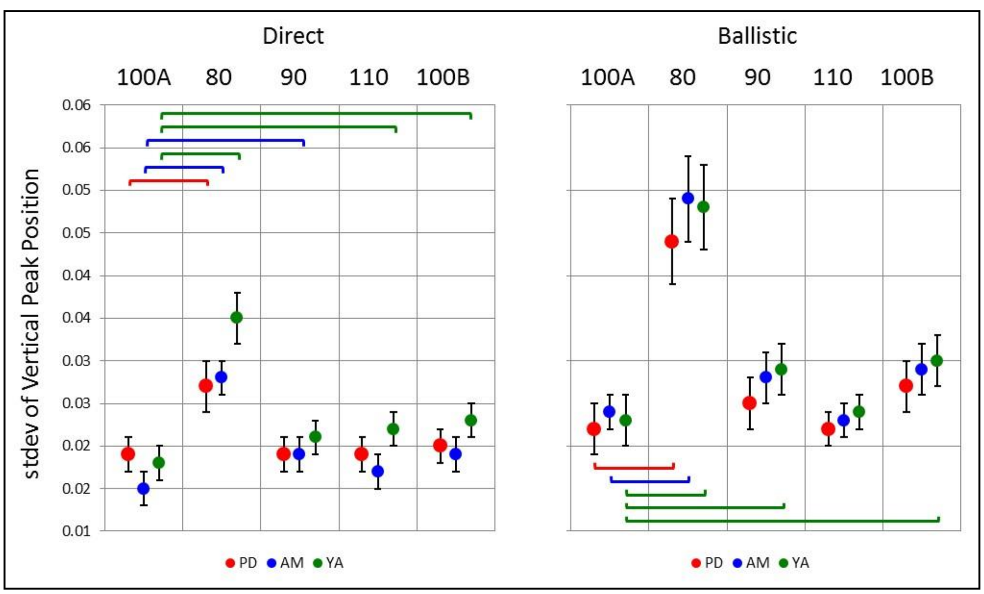

Figure 48. Standard Deviation of the Vertical Peak Position for Each Target for Direct and Ballistic Feedback.
Velocity Measures: Std_{aPeakY}. Comparison: Target. Legend as described in Figure 25.
a) Each group showed a higher standard deviation in the vertical peak position the 80 target compared to the 100A target.

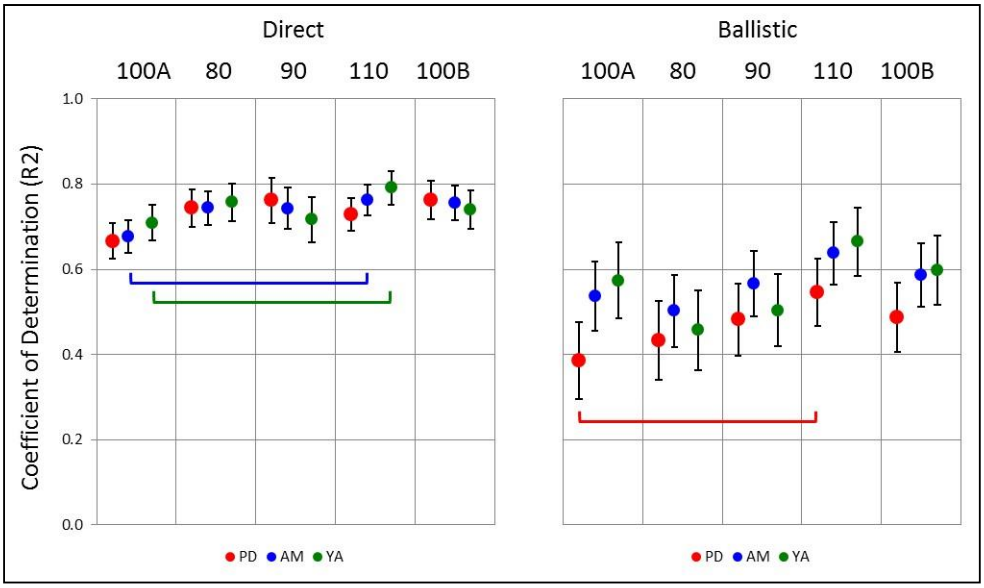

Figure 49. Reciprocity for Each Target for Direct and Ballistic Feedback.
Velocity Measures: Recip. Comparison: Target. Legend as described in Figure 25.
a) AM and YA were more reciprocal in direct feedback 110 target than 100A target.
b) PD was more reciprocal in the ballistic feedback 110 target than 100A target.

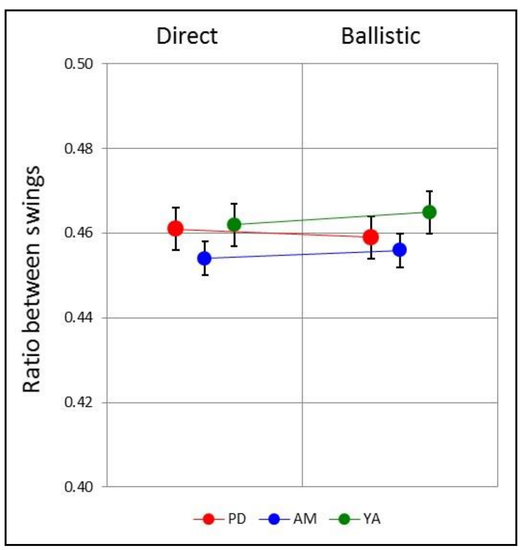

Figure 50. Timing Symmetry for Direct and Ballistic Feedback.
Velocity Measures: Sym (Timing). Comparison: Feedback. Legend as described in Figure 25.
a) No statically difference between direct and ballistic.

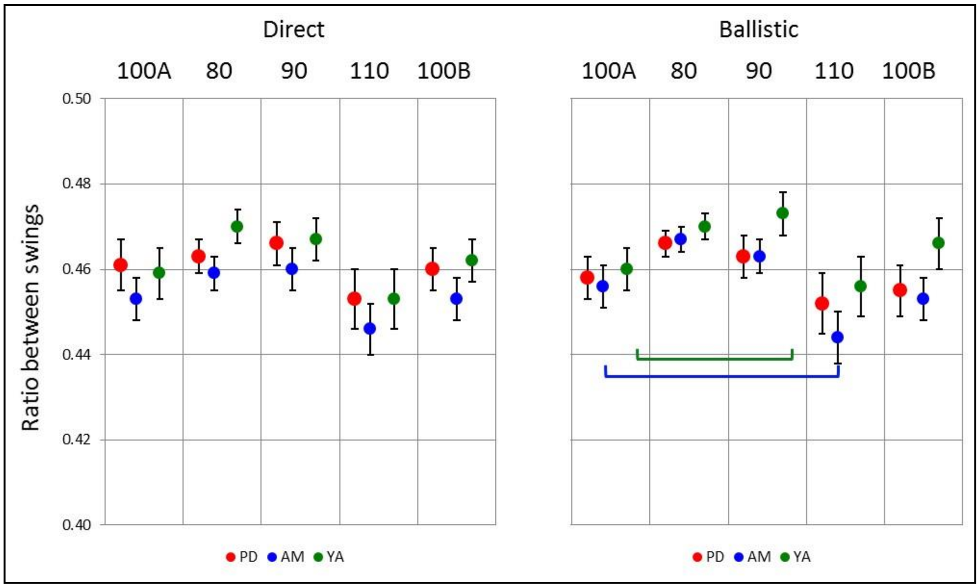

Figure 51. Timing Symmetry for Each Target of Direct and Ballistic Feedback.
Velocity Measures: Sym (Timing). Comparison: Target. Legend as described in Figure 25.
a) For direct feedback, first trial, YA had a smaller midpoint deviation than YA.
b) For ballistic feedback, first and last trial, YA had a small midpoint deviation than YA.

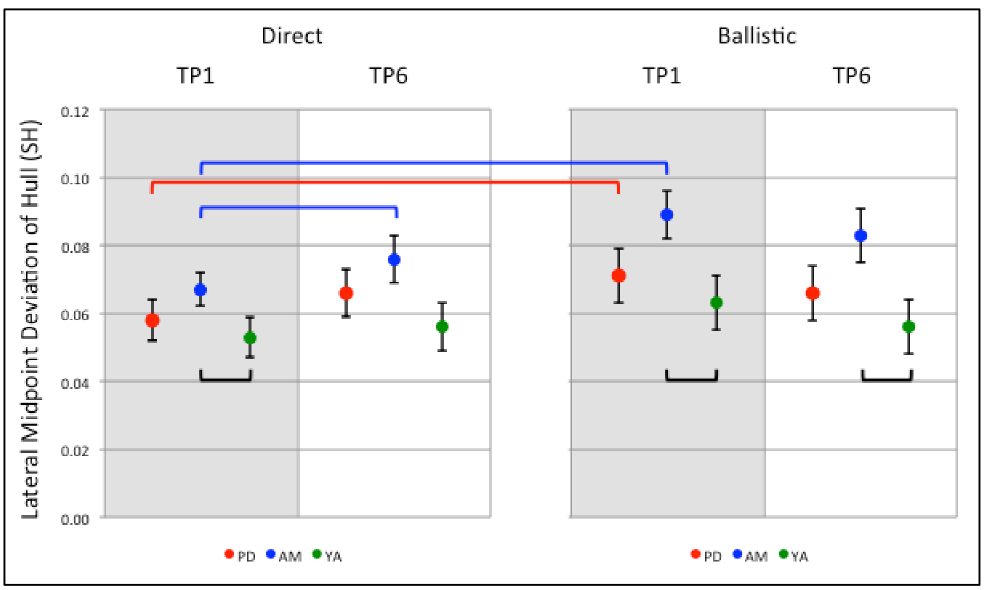

Figure 52. Lateral Midpoint Deviation of the First and Last Target Presentation of Direct and Ballistic Feedback
Velocity Measures: Dev_{mid}. Comparison: TP (First/Last). Legend as described in Figure 25.
a) For direct feedback, first trial, YA had a smaller midpoint deviation than YA.
b) For ballistic feedback, first and last trial, YA had a small midpoint deviation than YA.