THE EFFECT OF A MULTIMODAL EXERCISE INTERVENTION ON INTERLIMB COORDINATION IN INDIVIDUALS WITH PARKINSON'S DISEASE

by

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The Effect of a Multimodal Exercise Intervention on Interlimb Coordination in Individuals with Parkinson's Disease

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ABSTRACT

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George Mason University, 2020

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Background

Interlimb coordination, between arms, legs, and arm – leg pairs, is affected by Parkinson's Disease. The impaired coordination is not the result of slower gait speed, a common characteristic of Parkinson's gait, but a result of the reduction of scaling and amplitude of movement. Interlimb coordination assists in the regulation of angular momentum about the body's center of mass, by providing cancellation of the momentum generated, especially in the transverse and sagittal planes. Inclusion of coordinative exercises in interventions to improve balance and gait for individuals with PD has been emphasized in the literature, but not often reported as an objective outcome. The primary aim of this study was to investigate the effect of a 24 session performance-based gait training program on interlimb coordination for individual with Parkinson's Disease.

Methods

Individuals with mild to moderate PD were recruited to participate in a 24 session multimodal exercise training program. Each session focused on full body movements at a moderate intensity for 60 minutes twice a week. Participants were fitted with six inertial measurement units and completed a 10 minute walk test overground before and after the intervention. The primary and secondary outcomes were interlimb coordination, as measured by the point estimate of relative phase and the phase coordination index, speed, distance, and cadence. Coordination was calculated between arm, leg, and contralateral arm – leg pairs, accounting for the more affected (MA) and less affected (LA) sides.

Results

13 participants (7 males) completed the 24 session program. Leg coordination did not change between pre-(170.75±17.20°) and post-(169.24±20.83°) assessments. Coordination between arms improved from 161.52±8.72° to 168.08±9.63°, Phase Coordination Index (PCI) (10.37 ± 4.86% to 7.13 ± 5.01%). The more affected arm – leg pair was closer to in-phase (25.3±12.2° vs 19.1±9.3°), while the less affected pair maintained the phase relationship (19.2±12.6° vs 20.1±11.8°). Distance (89.32±77.20m), speed (0.14±0.12m/s), and cadence (6.2 steps/min) increased. Speed was correlated to MA coordination at the pre- ($r = -0.4731$) and post- ($r = -0.6455$) assessment. LA correlated to speed only at the pre assessment ($r = -0.5133$).

Discussion

Coordination between the leg – leg pair was not different between pre- and post-assessment, however, coordination improved between arms. Coordination between the more affected arm – leg pair improved, but was not altered for the less affected pair. Speed and cadence were not correlated to coordination between arms or between legs at either assessment, but were related to the coordination between the more affected arm – leg pair.

Conclusion

This pilot study provides preliminary evidence that interlimb coordination between arms and arm – leg pairs is improved after a multimodal, moderate intensity, exercise training program.

CHAPTER ONE

Introduction

Parkinson's Disease (PD), a progressive neurological disorder, impacts an individual's mobility, and their ability to perform daily tasks. It is estimated that in 2020, there will be 930,000 individuals 45 years or older with PD, increasing to 1.238 million in 2030.[1] For individuals with PD, arm-leg coordination, both the ipsilateral and contralateral pairs, is reduced,[2,3] and is correlated with poorer clinical scores of gait and posture.[2] Coordination during gait can be defined as "an ability to maintain a context-dependent and phase-dependent cyclical relationship between different body segments…in both spatial and temporal domains."[4] Phase relationships describe the symmetrical or asymmetrical, i.e. in-phase or out-of-phase, timing of minima and/or maxima, i.e., the instant of maximal flexion, between cyclical moving bodies, and describe the coordination of movement.[5–9] These cyclical relationships are present between interlimb pairs, whether it be between the arms, the legs, or between ipsilateral and contralateral arm and leg pairs.

The contralateral arm and leg swing show an in-phase relationship during locomotion, so that at the moment of heel strike, the contralateral arm is expected to be at or close to the moment of maxima of forward swing.[10,11] When walking at a comfortable to fast gait speed, the coordination between contralateral arm-leg pairs show a 1:1 swing ratio.[5,10,11] The strongest coupling of interlimb pairs is found between the cyclical swinging motions of the legs, regardless of walking speed,[10] but the importance of the relationship between the leg and arms and between arms should not be over looked. Interlimb coordination provides an avenue for the angular momentum about the body's center of mass (CoM) to be minimized. Angular momentum is kept low during gait by cancellation, especially in the transverse and sagittal plane by the relationship between the upper and lower body and the between the swinging motion of the right and left leg, respectively.[12]

The majority of the body's angular momentum is generated by the arms and legs, with the contribution from the arms increasing from 25% with speed while the legs remain constant, to around 60%, with no significant change in total angular momentum.[13] The swinging motion of the arms generates rotation about the vertical axis and in the direction of progression to counter angular momentum produced by the legs and trunk, and is important to forward progression during gait.[14] The control over total body angular momentum with increased speed is accomplished by balancing the arm and leg movements so as to increase the angular momentum from arm swing to account for the increased angular momentum generated by the legs.[13] This balancing act accomplished by opposing limbs within either plane highlights the benefits of cyclical movement symmetry between limb pairs and their importance to provide supportive and propulsive roles while walking.

Suppressing arm swing in healthy adults, either by binding or holding arms to prevent swing, decreases both gait speed[15] and step length.[15,16] Arm swing suppression also leads to an increase of CoM vertical displacement.[16] The increase of vertical displacement is accompanied by increases of ground reaction moments.[17] Without the momentum generated by the swinging of the arms to provide cancellation of momentum produced by the legs, total body angular momentum increases.[12,17,18] These factors are thought to be related to the metabolic cost of walking, thereby influencing the economy of gait.[10,17,19] This evidence highlights the influential role of both the arms and the legs during gait, and the importance of the out of phase coupling between limb pairs.

Interlimb coordination between legs[5,20–22] and between arms[20,23] is reduced in even the mild to moderate stage of PD. Although gait speed influences the strength of interlimb coordination[24,25] and individuals with PD tend to walk at slower speeds, the reduction of coordination is not due solely to the slower speeds.[20,26] There is evidence that walking economy is also compromised,[27,28] with poorer economy related to greater disease severity in the mild to moderate stages.[27] Since the swinging movement of the arms provide cancellation of angular momentum about the CoM,[12,29] and the suppression of arm swing increases the metabolic cost of gait,[17] it is possible that the alterations in coordination influence the alteration in walking economy.

Attentional strategies, such as visual, auditory, and haptic cuing, have been used to explore the influence of arm swing manipulations on gait characteristics. When individuals with PD were instructed to deliberately swing their arms, arm swing amplitude increased as did gait speed and step length.[30] In a separate study, haptic cues (i.e., vibration to the wrist), and visual cues for arm swing magnitude resulted in increased step length during trails while either cue was present.[31] The results of these studies provide evidence that increased arm swing can alter the characteristic slow gait speeds and shorter steps so often associated with PD.

There is limited evidence that describe the effects of gait retraining on coordination because the majority of studies focused on manipulations of speed, dual task, and direction.[32] A robotic assisted gait training for freezing of gait[33] and a comparison of balance or resistance training on postural control[34] have investigated interlimb coordination, between legs, as a secondary outcome measure, with mixed results. The importance of interlimb coordination to gait and stability has been emphasized as important to include in gait interventions designed for PD.[35–37] Interventions aimed at increasing mobility and gait quality should include exercises of sufficient and sustained intensity, with specificity to the activity, but also variability of practice as well as progressing the difficulty and complexity of practice to induce change of performace.[37,38]

Specific Aims

Our overall research question was how are interlimb coordinative patterns affected by gait training programs in individuals with Parkinson's Disease. Therefore, we proposed to conduct this pilot study with two specific aims.

Specific Aim 1: Investigate the effect of a 24-session performance-based gait training program on interlimb coordination for individuals with Parkinson's Disease as evidence by PERP and PCI.

H1: After completion of the training program, interlimb coordination will become more tightly coupled, out of phase for arm-arm and leg-leg pairs, while in-phase for contralateral arm-leg pairs during overground gait.

Specific Aim 2: Characterize the relationship between spatiotemporal gait measures and interlimb coordination, as measured by PERP and/or PCI, during an extended overground walking test.

H2: Individuals with Parkinson's Disease will begin the 10 minute walk with more closely coupled interlimb coordination than that will progressively become less tightly coupled by the end of the assessment.

Methods

This was a pilot study and describes the first cohort of participants to complete the training program in individuals with Parkinson's disease. Both the assessments and the training sessions were conducted in the Functional Performance Lab of George Mason University (Fairfax, VA).

The study recruited participants from local Parkinson's Disease support groups in the northern Virginia and greater Washington D.C. area and by word of mouth. All participants were classified as Hoehn & Yahr (H&Y) stages 1-3, with an average age of age 68.4±6.1 years (Table 1). Participants were consented and screened for eligibility criteria. Eligible participants were over the age of 18, had a diagnosis of Parkinson's Disease, in the mild to moderate stage as determined by the Hoehn & Yahr (H&Y; stages1-3), able to speak and comprehend English, and able to ambulate without the use of an assistive device.

Individuals were excluded if they had a neurological disease diagnosis other than PD, an uncontrolled cardiovascular, neurological pulmonary, or metabolic disease that could impact the ability to exercise or where exercise is contraindicated, any medications (ex. Beta-blockers) that may alter heart rate, any cognitive or psychiatric impairment precluding informed consent or ability to follow directions, a mini-Mental State Examination score of <24, pregnancy, or the inability to ambulate without the use of an assistive device. This study was approved by the GMU IRB (#13746151) and registered as a clinical trial (NCT03864393).

Figure 1 Study Protocol

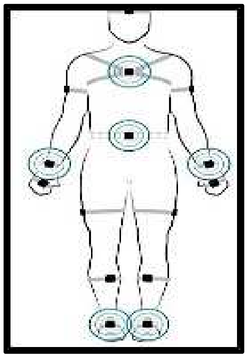

Figure 2 Template for IMU sensor placement
Blue circles highlight sensors used in assessment. *Note*: The approximate anterior location of the lumbar sensor is shown, but the sensor was secured approximately at the 4th lumbar vertebra.

Study Protocol

There were 26 total visits required to complete the study. Visits 1 and 26 were the pre- and post-assessment, respectively. Visits between assessments (visits 2 – 25) comprised of 24 individual 60 minute exercise training sessions. A flowchart of the research study describes the number of participants who completed each phase (**Figure 1**). Of the 15 participants who consented, 13 completed the study protocol (1 screen fail;1 drop out).

Assessment Procedure

Pre- and post-assessments started by collecting the participants height, weight, age, H&Y (pre-assessment only), and noting the more affected side. At the pre-assessment, participants were then randomized to a testing order, that determined either the 10 minute walk test (10WT) or Motion Capture Gait assessment as the first. The order of testing was consistent for both pre and post assessment for each participant. Each participant completed the assessments at approximately the same time of day to control for the effects of levodopa on gait parameters.[26,39] Between the 10WT and Motion Capture Gait assessment there was a 20 minute resting period.

Ten Minute Walk Test

Participants were fitted with six opal wearable sensors (APDM, Portland, USA) that record synchronized logged data from triaxial accelerometer, gyroscope, and magnetometer in each inertial measurement unit (IMU) sensor. Sensors were secured via velcro strap to each wrist, the top of each shoe, the sternum, and approximately the 4th lumbar vertebra (**Figure 2**). The walkway was 60 meters long with a meter distance on either side for the participant to turn around, a 180 degree turn. Participants were instructed to walk as many laps as possible in the designated 10 minutes.

Participants stood still with their arms at their side prior to the start of the 10WT. At 150 second intervals (a quarter of the total time, 2.5 min) and at the end of the ten minutes, distance traveled was recorded. The instructions given during the 10WT were to "complete as many laps as you can until you hear 'stop'", with no indication given to the participants on how many minutes have passed. At the end of the 10 minutes, a testing administrator said "stop" and participants were instructed to stop walking. The beginning of the assessment, including the quiet standing before the test, and end of the test were marked with event markers from the right wrist sensor. Only straight-line walking was used in further analysis, the process of removing turns from the data is described below.

Exercise Training Program

The intervention was a multimodal exercise training program targeting gait economy through moderate intensity exercises utilizing full body movements. Each session was approximately 60 minutes in duration and focused on specific aspects of walking. The program was designed using the performance-based framework for overground locomotor training, emphasizing specificity, progressive overload, and practice variation.[38]

Sessions alternated between forward, backward, rotational, and lateral directionally based exercises that targeted full body movement. The focus of sessions was either steady state gait (SSG) or gait initiation (GI), while the emphasis was power, swing, or stability. The direction, focus, and emphasis of the session varied from session to session in a set order. Each session began with a progressive warm up followed by an integration phase, which progressed from part to whole practice incorporating the focus and emphasis of each session. The final part of each session was rehearsal. These sessions were divided into three phases. Volume, speed, resistance, and complexity of task were manipulated over each phase. Sessions were led by research personnel trained to lead exercises and study safety procedures. The exercises training sessions can be found in **Appendix II**.

Data Analysis

Raw sensor data were imported into Matlab 2017b (Mathworks, Natick, MA) for post processing. Data were trimmed to only include the ten minutes of walking. Turns were removed from the data by utilizing the integrated lumbar gyroscope signal in the determination of the start and end of a turn (**Figure 3**).[40] All turns performed during the completion of this assessment were 180°, although it was up to each individual which direction to turn. The number of turns identified was confirmed by comparison to the turns recorded on the data collection sheet.

After turns were removed, data from the gyroscopes were filtered using a low pass zero-phase Butterworth filter with a 5Hz frequency cutoff. Gait events were calculated from the foot mounted gyroscopes[41] (**Figure 4**). During single leg stance, the angular velocity for rotation about the z axis is near zero. Heel strike is the moment of the minima prior to the near zero angular velocity period, where toe off is the minima after this period. Swing phase is width of the peak following toe off. Heel strike events, the timing of right and left steps, were used to calculate the amount of steps taken over the entire walkway length. The last walkway length completed in each section was used to calculate cadence. Timing of the first and final steps determined the time interval (in seconds). Number of steps taken over that time interval resulted in steps per second, which was converted to steps per minute (cadence). Cadence for the 10WT was calculated as the average cadence of each of the four 2.5 minute sections. Heel strike events and the swing duration of each leg were used in coordination calculations.

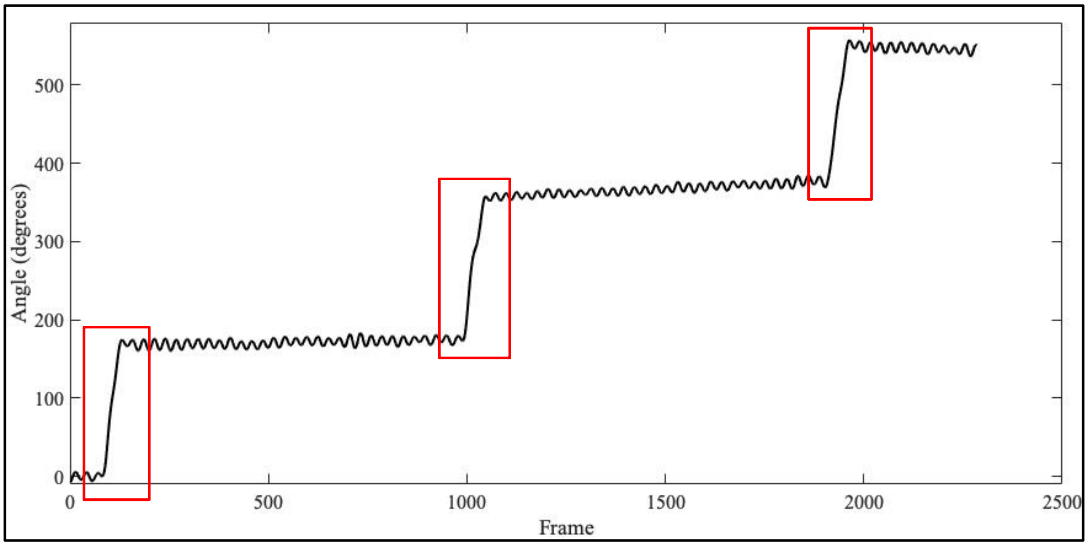

Figure 3 Turn determination
Integrated gyroscope signal (°) from the lumbar IMU shows timing of turns during 10WT. Highlighted sections illustrate turns at the end of the corridor.

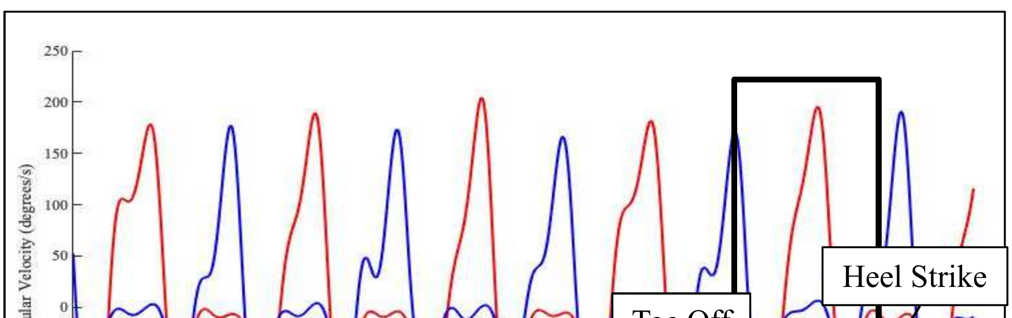

Figure 4 Gait Events Determined by Foot Mounted Gyroscope
Illustration of right (**red**) and left (**blue**) foot gyroscope (°/s) used to determine heel strike and toe off events. *Note:*(*) indicates heel strike, • indicates toe off

Arm swing was calculated from the sensors attached to the wrist with the lumbar sensor as a reference. Unfiltered data from the accelerometer, gyroscope, and magnetometer were fused together to produce an orientation quaternion using the method Madgwick et al. described for each sensor.[42] The orientation quaternion was converted to Euler angles. Yaw (angle) was used to describe arm swing, wrist movement in the sagittal plane (see **Figure 5**). Magnitude and timing of peaks were calculated for each arm. Values from the first and final two strides removed from the data to account for acceleration and deceleration of gait. The timing of peaks was used to calculate arm – arm and arm – leg coordination. To compare contralateral limb pairs, the more affected arm was paired with the less affected leg (MA), while the less affected arm was paired with the more affected leg (LA). The instants of heel strike and arm swing maximum for the contralateral arm and leg were used to calculate the coordination between upper and lower limbs (**Figure 6**).

Coordination was calculated as the point estimates of relative phase (PERP; °).[10] Due to the cyclical movement of both the arms and legs during locomotion, the instances of key events ($t_{limbx} and\ t_{limby}$), heel strike for legs and peak sagittal plane movement for arms, were used to determine the phase relationship between the two limbs (Eq 1).

Equation 1

$$\Phi_{(i)} = \frac{t_{limby(i)} - t_{limbx(i)}}{t_{limbx(i+1)} - t_{limbx(i)}} \times 360$$

The limb with longer average swing phase duration represented *limb*$_x$, the shorter duration described as *limb*$_y$, in calculation of coordination between legs.[21] Longer and shorter arm phase durations were designated as $limb_x$ and $limb_y$, respectively. Standard deviation of the relative phase, SD Φ, measured the variability of the phase generation, i.e. the stability. The Phase Coordination Index (PCI), a measure that accounts for the accuracy (Eq 2; °) and consistency (Eq 3; %) of Φ, where a value of 0 describes exact and consistent anti-phase cyclical movement between contralateral limbs, was used to measure out of phase limb coupling.[21] PCI was also calculated for arm swing .[43] Outcome measures were calculated for the total, as well as each of the four 2.5 minute sections of the 10WT.

Equation 2

$$\Phi\ ABS = \overline{|\Phi_\iota - 180°|}$$

Equation 3

$$\Phi\ \mathrm{CV} = \frac{\delta}{\overline{\Phi}}$$

δ= standard deviation of Φ; $\overline{\Phi}$= mean of Φ

Equation 4

$$\mathrm{P}\Phi\ ABS = 100 \times (\frac{\Phi\ ABS}{180°})$$

Equation 5

$$PCI(\%) = \Phi\ \mathrm{CV} + \mathrm{P}\Phi\ ABS$$

Statistical Analysis

Descriptive statistics were calculated for demographic data and all outcome variables. Student paired t-tests were used to assess change of speed, cadence, and coordination measures after completion of the intervention. Pearson correlation coefficients were calculated to determine the relationship between interlimb coordination measures, gait speed, and cadence over the total 10WT, as well as the first and fourth section. Bonferroni post hoc analysis was completed if significance was found. Statistical analysis was performed using STATA (*Version 12, College Station, TX)*.

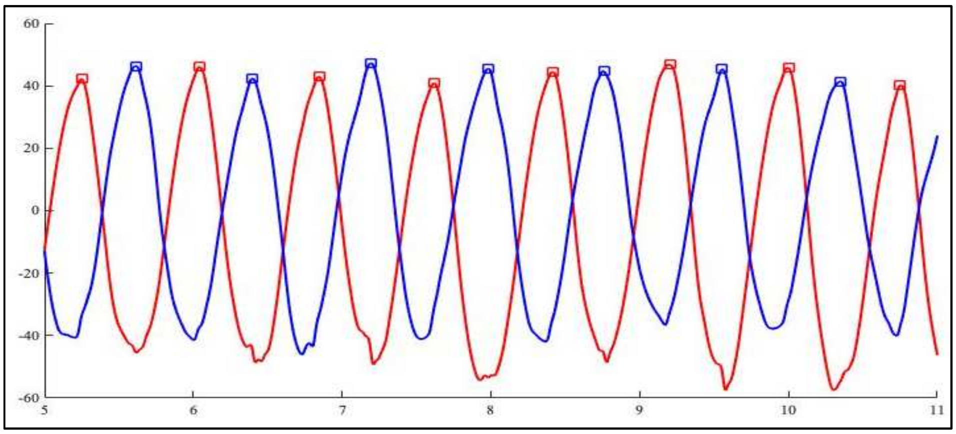

Figure 5 Arm Swing
Angle of the wrist in relation to the lumbar sensor that were used describe arm swing during 10 minute walk. *Note:* The right (**red**) and left (**blue**) arms are shown with the peaks (squares).

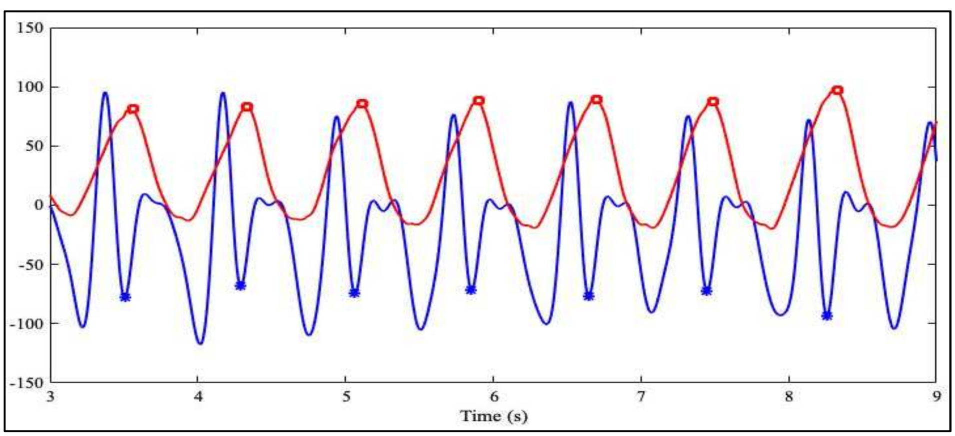

Figure 6 Contralateral Interlimb Coordination
Coordination of the left foot(**blue**; °/s) and right arm (**red**; °). *Note:* Maximum arm flexion denoted by ; heel strike denoted by *;

Results

Demographic characteristics are described in **Table 1** for the 13 participants who completed the study protocol. One participant sustained a lower limb injury, unrelated to participation in the study, that necessitated a several week delay between session 15 and 16. This participant was able to return and complete sessions 16-24.

Table 1 Participant Demographic

Participant	*Age (years)*	*Gender*	*Height (cm)*	*Weight (kg)*	*H&Y*	*Affected Side*
1	71	M	176.5	74.7	1	R
2	71	M	176.5	79.4	1.5	R
3	67	F	163.0	53.7	1.5	R
4	76	F	174.0	61.8	1	R
5	64	M	180.5	76.3	1	L
6	75	M	168.5	77.0	2	R
8	55	F	150.0	51.7	2	R
9	70	F	156.75	46.0	2	R
10	74	M	161.5	74.8	3	R
11	65	M	164.3	65.8	2	L
12	65	F	160.9	55.6	2	R
14	62	M	169.0	79.4	2	L
15	74	F	164.7	65.9	2	L
Avg(SD)	**68.4(6.1)**	**7M**	**166.6(8.7)**	**66.3(11.6)**	**1-3**	**9R**

Interlimb Coordination

Measures of interlimb coordination, specifically PERP (Φ), stability (Φ SD), PCI, accuracy (Φ abs), and consistency (Φ cv), for the 10WT are described below in **Table 2**. A breakdown of these variables by 2.5min sections (1=start-2.5 min; 2=2.5-5 min; 3=5-7.5 min; 4=7.5-end) of the 10MW is provided in **Appendix III**. The following sections describe the results for Arm–Arm, Leg–Leg, and MA/LA Arm – Leg separately. Tremor prevented calculation of a seperate participant's arm swing. This participant excluded for arm – arm and arm – leg analyses.

Table 2 Coordination over 10WT
Summary of Arm – Arm and Leg – Leg coordination. *Note:* Φ = PERP; PCI = Phase Coordination Index; *pre-post p<0.05

Outcome	**Arm – Arm**		**Leg – Leg**	
	Pre	*Post*	*Pre*	*Post*
Φ	161.5 ± 8.72	169.7 ± 11.9*	170.8 ± 17.2	169.2 ± 20.8
Φ SD	16.5 ± 8.3	14.6 ± 4.4	9.5 ± 6.1	9.2 ± 9.1
PCI	10.4 ± 4.9	7.1 ± 5.0	5.6 ± 9.4	7.0 ± 11.0
Φ abs	18.5 ± 8.7	12.7 ± 9.0	9.9 ± 16.8	12.6 ± 19.7
Φ cv	0.10 ± 0.053	0.086 ± 0.025	0.058 ± 0.041	0.056 ± 0.055

Leg – Leg Coordination

No significant change in leg – leg coupling was observed as a result of participation in the intervention. There was a large range observed in PERP present at both pre- 170.75±17.20° and post- 169.24±20.83° assessment. Stability of phase generation was equivalent at each assessment, 9.52±6.11 to 9.21±9.14 (p=0.9130). Since relative phase failed to close the gap to 180°, accompanied by lack of change in the strength of coordination, as measured by PERP, was equivalent. PCI increased from 5.57 ±9.35% (0.11-32.87%) to 7.04±10.96% (0.16-32.85%), a result of reduced accuracy, Φ abs 9.92±16.79 to 12.58±19.70, and consistency, Φ cv 0.058±0.041 to 0.056±0.055, of the stepping phase. **Figure 7** describes the changes in PCI by participant, with positive values indicating the PCI moved away from 0.[21] The participant that sustained an unrelated lower limb injury showed a significant increase of leg-leg coordination measurements (ΔPCI = +24%), and was an outlier. Excluding that participant (N=12), PERP increased from 170.15±17.8° to 172.10±18.9° (p=0.1689), with no alteration in stability (0.54±10.51; p = 0.8609). Lack of change in accuracy (0.71±3.95; p=0.5444) or consistency (0.004±0.06; p=0.8306) of the relative phase was reflected by the PCI values observed at the pre (5.93±9.67%) and post (5.54±9.94%) assessments (p=0.5431).

Arm – Arm Coordination

PERP between the arm-arm pair for the 10WT was 161.52±8.72°, with a minimum value of 145.23°, for the pre-, while 168.08±9.63°, minimum of 151.17°, at the post-assessment (p=0.0460). The stability of coordination(ΦSD) was equivocal (p=0.4764) between the pre-, 16.45±8.34 (range 7.40-35.30), and post-assessment, 14.62±4.39 (range 10.16-22.89). The PCI decreased, from 10.37±4.86% (range 0.60-19.46%) to 7.13±5.01% (range 0.85-16.10%), though the trend did not reach significance (p=0.1044). Accuracy improved ($\bar{x}$=5.8±11.4; p=0.1070) without significant change of consistency, which resulted in better coordination, as measured by PCI. These results indicate that interlimb coordination improved, with accuracy of the phase generation, over the 10WT.

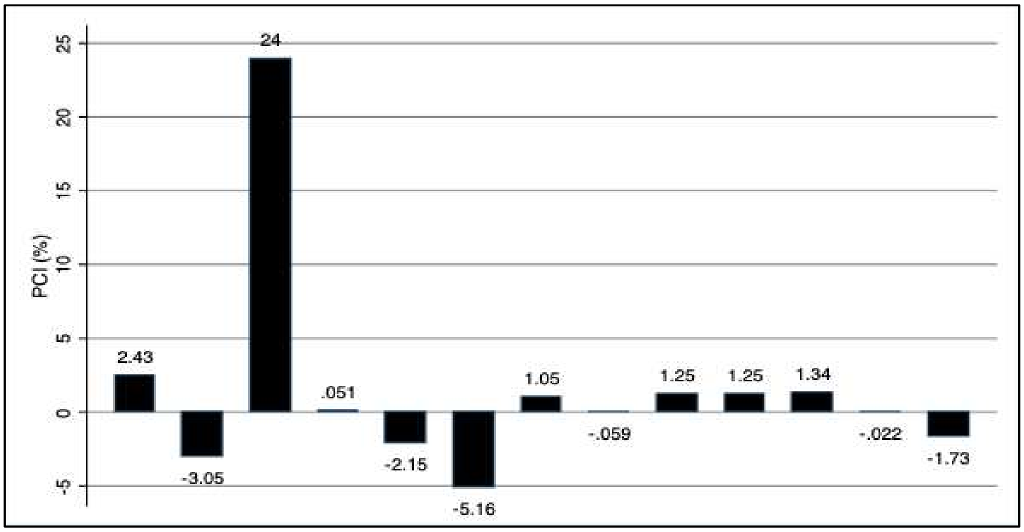

Figure 7 Leg PCI
Difference of PCI (%) from pre- to post-assessment by participant. *Note*: negative values indicate PCI decreased

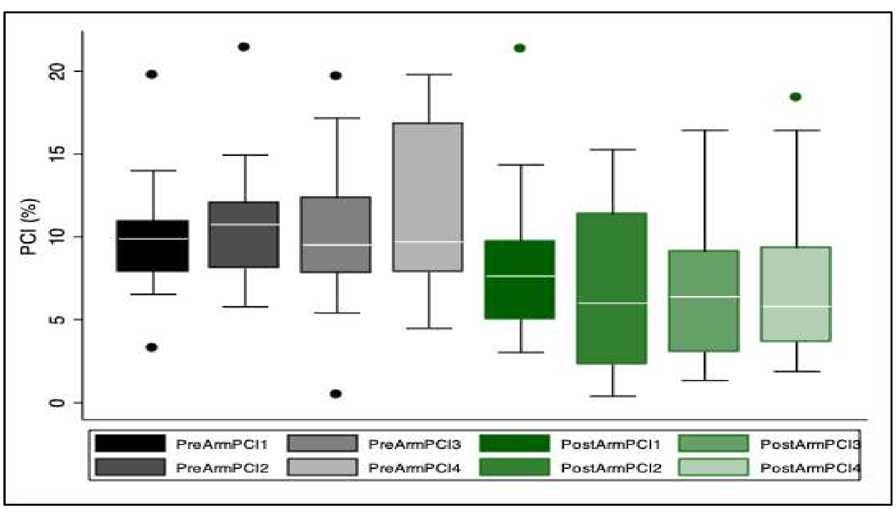

Figure 8 Arm – Arm PCI by 10WT Section
Boxplot describing the lower and upper quartiles, minimum, median, maximum and outliers of Arm PCI for each 2.5 minute section during the pre- (**grey**) and post-assessment (**green**)

Over the duration of the 10WT section 1 to section 4, Φ decreased by 5.1±10.7° and 1.2±12.1° for the pre- and post- assessment, respectively. PERP was closer to the ideal out of phase relationship of 180° during the first section and was maintained throughout the duration of the 10 minutes. **Figure 8** illustrates PCI for each of the four 10WT sections both before and after the intervention. During the pre-assessment (shades of black), the inter-participant variability increased over the 10 minute duration, even though there was a not a significant difference in the group mean at each time point. PCI remained similar throughout the post assessment as well, though there was not a significant difference between the values measured during each assessment.

Arm – Leg Coordination

A participant with an unrelated injury was excluded for arm–leg analyses. Interlimb coordination between arm–leg pairs were grouped by the more affected (MA) and less affected (LA) arm with the contralateral leg (**Table 3**).

Table 3 Arm – Leg Coordination
Coordination of more affected (MA) and less affected (LA) pairs; *pre-post $p<0.05$

Outcome	**Pre**		**Post**	
	MA	***LA***	***MA***	***LA***
Φ Total	25.3 ± 12.2	19.2 ± 12.6	19.1 ± 9.3	20.1 ± 11.8
Φ 1	24.8 ± 13.3	20.8 ± 10.9	16.1 ± 9.3*	16.9 ± 12.3
Φ 2	24.2 ± 14.5	19.8 ± 13.1	20.0 ± 10.6	18.2 ± 10.3
Φ 3	25.5 ± 12.0	17.5 ± 10.6	18.6 ± 8.9	23.2 ± 13.7
Φ 4	26.7 ± 12.6	18.0 ± 17.6	21.6 ± 10.4	22.4 ± 13.5
Φ SD Total	10.8 ± 3.1	9.9 ± 4.5	9.4 ± 3.0	9.9 ± 5.1
Φ SD 1	9.8 ± 3.8	9.8 ± 5.8	7.0 ± 1.9	9.2 ± 5.3
Φ SD 2	7.9 ± 2.6	8.3 ± 5.3	10.5 ± 4.2	8.9 ± 4.6
Φ SD 3	10.7 ± 3.5	8.6 ± 4.2	8.1 ± 2.9	9.7 ± 5.4
Φ SD 4	10.2 ± 3.1	7.5 ± 3.2	8.9 ± 3.1	7.4 ± 3.9

There was not a significant difference between the PERP after completion of the training program. Comparison of the MA versus LA PERP revealed no significant difference at either the pre-, where MA was 6.1±18.1° greater than LA ($p=0.2898$), or post-, where MA was 1.0±15.0° less than LA ($p=0.8279$), assessments. **Figure 9** illustrates MA and LA PERP over the 10WT at both assessment time points. There was a large amount of group variability observed in PERP for both the MA and LA pairs. Stability of PERP was not significantly different between the first and fourth sections at either assessment. This was true for both the MA and LA pairs. Though changes were not significant, **Figure 10** depicts the decrease of MA variability in both sections after the intervention, but an increase of variability from section 1 to section 4 at the post-assessment. The LA variability decreased between section 1 and 4 during both assessments.

The tighter the out-of-phase relationship was between legs, i.e. PERP closer to 180°, the closer the LA contralateral arm – leg pair ($r = -0.6355$; $p=0.0356$), but not the MA pair ($p>0.6$), was to 0 at post-assessment. A similar correlation between arm – arm ΦSD and LA PERP ($r = 0.6973$; $p=0.0171$) was found after completion of the intervention. These relationships were not observed at pre-assessment.

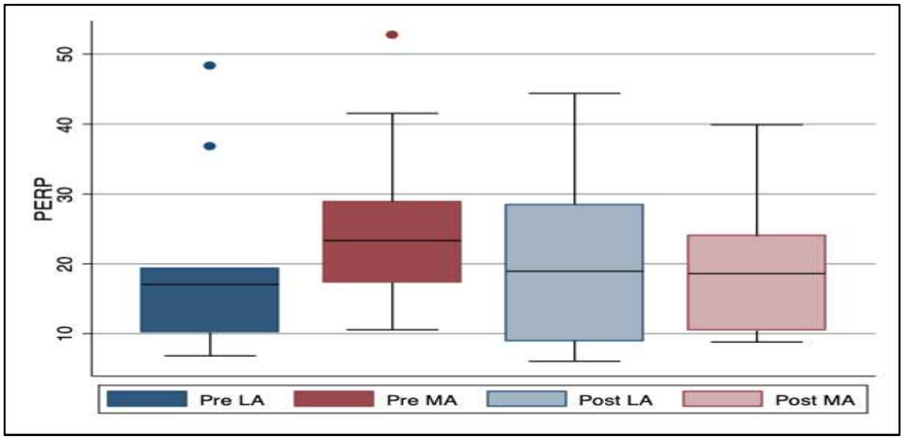

Figure 9 Arm – Leg PERP

Boxplot showing the lower and upper quartiles, minimum, median, maximum and outliers of Φ over the 10WT pre- (darker shade; left) and post- (lighter shade; right) assessment. *Note:* MA (**red**) ; LA (**blue**)

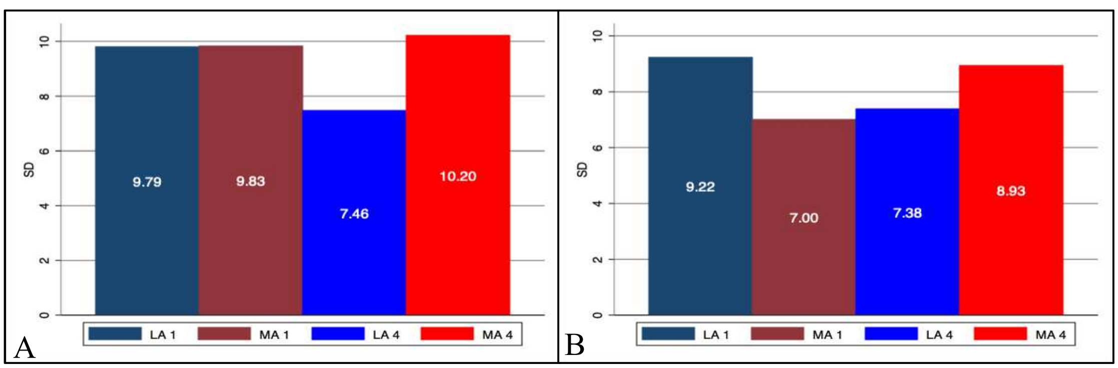

Figure 10 Arm – Leg ΦSD

The ΦSD of contralateral arm – leg pairs in the first 2.5 min section (1) and final 2.5 section (4) of the 10WT at **A**) pre- and **B**) post-assessment. *Note:* LA (**blue**); MA (**red**)

Speed, Distance, and Cadence

Table 4 Distance and Speed 10WT
Average speed,distance during 10WT, total and by each 2.5 min section (1-4); *p<0.05

10 Minute Walk Test		Pre-Assessment			Post-Assessment		
		Speed (m/s)	Distance (m)	Cadence (steps/min)	Speed (m/s)	Distanc e (m)	Cadence (steps/min)
1	Mean	1.46	218.98	128.0	1.63*	244.78*	134.3*
	SD	0.25	37.28	13.1	0.24	35.43	11.3
2	Mean	1.46	218.28	127.9	1.60	239.84	133.7
	SD	0.25	37.10	14.2	0.23	34.00	11.6
3	Mean	1.47	220.32	128.0	1.61	242.21	134.3
	SD	0.26	38.53	14.8	0.22	32.96	11.6
4	Avg	1.49	223.24	128.3	1.62*	243.29*	134.6*
	SD	0.27	40.13	15.0	0.22	33.40	12.4
Total	Mean	1.47	880.81	128.0	1.62*	970.13*	134.2*
	SD	0.25	151.59	14.1	0.23	135.01	11.7

The cadence, speed, and distance covered during the 10WT, and in each 2.5 minute section, is summarized in **Table 4**. The distance covered over the 10WT increased from 880.81±151.59m to 970.13±135.01m, an average change of 89.32±77.20m (*p=0.0013*), shown in **Figure 11**. Accordingly, speed measured at the pre assessment (1.47±0.25m/s) increased by an average of 0.14±0.12m/s compared to the post assessment walking speed (1.62±0.23m/s). There was no difference in speed between the first and fourth 2.5 minute section. Cadence increased from 128.0±13.1 to 134.2±11.7 steps/min (p=0.0031). Similar to speed, there was not a significant difference in cadence between the first and fourth section at either assessment. Cadence was positively correlated with speed at pre- (r=0.8021; p=0.0017) and post-(r=0.6344; p=0.0267) assessment. This relationship is illustrated in **Figure 12**. The shift up of post-assessment markers reflects the increase in both measures after the intervention.

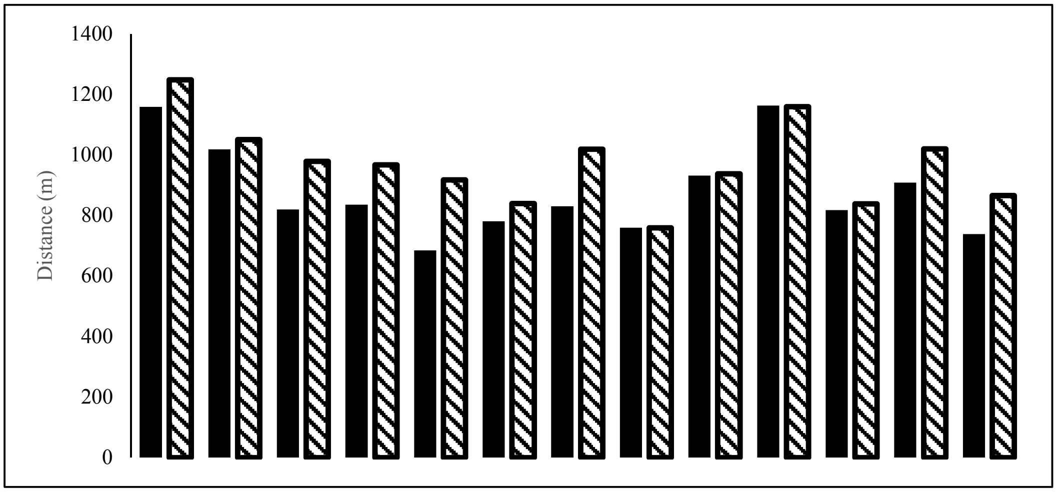

Figure 11 10WT Distance
The total distance covered by each participant over the 10WT for the pre (black) and the post-assessment (stripes).

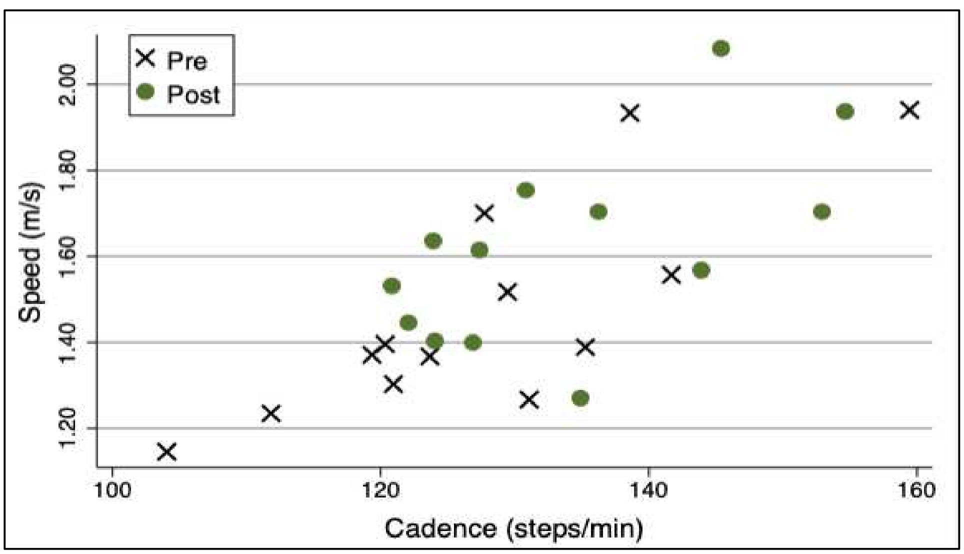

Figure 12 Correlation of Speed and Cadence
Speed was correlated with speed at both pre- and post-assessment ($p<0.05$).

Correlation between Interlimb Coordination, Speed, & Cadence

Cadence was associated with measures of interlimb coordination. At pre-assessment, cadence was negatively correlated to LA PERP (r = -0.5804;p=0.0612), LA ΦSD (r = -0.4914; p=0.1248), and MA PERP (r = -0.5097; p=0.1093). Only MA PERP and cadence were correlated after the intervention(r = -0.5965; p=0.0527). The correlations of cadence and PERP of both contralateral limb pairs are illustrated below in **Figure 13**. After completion of the intervention, speed was correlated with MA PERP (r = -0.6455; p=0.0320), while at the first assessment this was not significant (r = -0.4731; p=0.1417). The phase relationship of the MA pair was negatively correlated with gait speed at pre assessment (r = - 0.5133; p=0.1063), but not post-assessment (p>0.8). Neither LA nor MA Φ SD was correlated to speed at either assessment (p>0.45). During the pre-assessment, cadence was related to LA PERP (r = -0.6050; p=0.0486) and LA Φ SD (r = -0.7089; p=0.0146) in section 1. There was a similar trend found for MA PERP (r = -0.4649; p=0.1496) in section 1, as well as LA and MA PERP (r = -0.4960; p=0.1207; r = -0.4654; p=0.1491, respectively) in section 4, but the trends were not significant. Cadence was only correlated with MA PERP, in both the first (r = -0.6368; p=0.0351) and final 10WT (r = -0.5792; p=0.0619) sections, at the post-assessment.

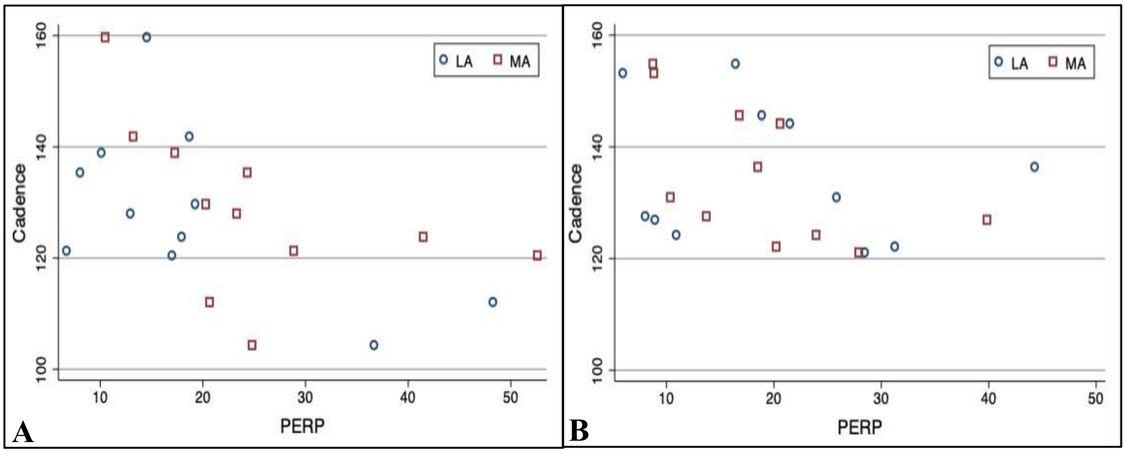

Figure 13 Correlation of LA, MA PERP and Cadence
Scatter plot of cadence (steps/min) and PERP (°) of MA(**blue**) & LA(**red**) at **A**) pre- and **B**) post-assessment

Discussion

This pilot study investigates interlimb coordination, both between homologous limb pairs and contralateral upper and lower limb pairs, as a primary outcome after an intervention in individuals with PD. There is abundant evidence that interlimb coordination is affected by PD, however, most of the literature has focused on characterization of coordinative patterns, effects of short term perturbations, or use coordination as a secondary measure.[2,3,5,20,23,44–48] In the present study, we were able to show a significant improvement in arm – arm interlimb coordination, but no change in coordination between leg and arm – leg pairs, after participation in the 24 session multimodal training program. Influence of the training program on interlimb coordination and spatiotemporal gait measures are discussed below.

Bilateral coordination of the lower extremities is sensitive to aging, slow gait speed, and dual tasks. Increased PCI values have been described for both older adults and individuals with PD. The values of leg – leg PCI, measured at both the pre- and post-assessments, were similar to those reported by Plotnik and collegues.[21] Although the authors reported PCI at a comfortable walking speed, both studies described gait overground and for longer durations, i.e., a 2 minute walk. The absence of significant change in values of PCI overall is similar to the results reported for resistance or balance exercise training programs to improve postural control,[34] and a robot assisted gait intervention to reduce freezing of gait.[33] Further research is needed to determine if specific modes of exercise, volume, or intensity improve leg PCI. Rhythmic auditory cuing could be an avenue to elicit a change in PCI due to the even timing between cues, and therefore stepping time.

Coordination between arms was improved at the post-assessment time point, as measured by PERP. Participants walked at their self-selected fast pace for ten minutes and maintained the selected speed over the duration of the testing period. A specific aim of this study was to explore if there were interlimb coordination changes from the first section to the final section. No significant change between arm relative phase was found over these two sections. The arms approached the ideal out of phase relationship after the 24-session program and maintained that tighter coupling. The stability of phase generation between arms was similar to that reported by Lin and Wagenaar (Φ SD 13.9±10.6), as participants with PD walked on a treadmill at 1.3 m/s.[20] Participants in the present study walked at a faster speed overground for a longer duration at both assessment time points. The swinging motion of the arms is important to the regulation of angular momentum about the CoM, especially at increased speeds.[12] Although angular momentum was not measured, tighter coupling between arms aids forward progression by opposing the rotation about the vertical generated by the lower limb and trunk.[14]

The primary goal of the 10WT is to cover as much distance as possible in the given time. Participants were not told to accomplish this task in a specific way (i.e. cadence, length of stride). This allowed investigation of individual movement solutions to accomplish the task. Unlike other investigations that have utilized a treadmill, which forces velocity to remain constant, participants walked overground for an extended time period without this constraint. Speed increased by an average of 0.15 m/s, with eight of the thirteen participants increasing speed by ≥ 0.10 m/s, after the intervention. This change is within the minimal to moderate meaningful change for individuals with PD in the "on" medication state.[49] Cadence also increased, and was strongly correlated to the observed increase of speed. Of those that increased their speed by 0.10 m/s or more, cadence increased by an average of 9.1 steps/min. The increase in speed, due partly to faster cadence, enabled participants to walk further at the post-assessment.

An interesting finding was that approach of the MA pair to the optimal in-phase relationship, i.e., closer to simultaneous timing of heel strike with the maximum point of the contralateral arm swing, was associated with gait speed in both assessments, though only statistically significant at the post assessment. It has been previously shown that coordination between ipsilateral arm–leg pairs for both the more and less affected side, with only the contralateral more affected arm and less affected shoulder, was significantly reduced when compared to age matched controls during overground walking, even when no significant difference in speed was present.[2] This study found that the MA pair, the more affected arm paired with the less affected leg, was related to gait speed in the study's sample. A larger sample size would be needed to perform more robust analysis to investigate these findings further.

There is evidence that supports the role of interlimb coordination in decreasing the metabolic cost of walking due to the cancellation of on angular momentum about the CoM, especially in the sagittal and transverse plane.[17,19,50] The association of tighter interlimb coupling, as measured by relative phase, with increased gait speed has been demonstrated in individuals with PD.[2,20,24] Arm swing was closer to an optimal out of phase relationship, with a positive trend for increased accuracy of the phase generation. In contrast, there was no change in the coupling between the lower limbs. The angular momentum generated by leg swing was greater at all speeds than produced by the arms, and the contribution of the arm increased with gait speed. In this context, it is possible that the arms that are able to provide a greater cancellation of angular momentum, and thus an increased speed was achieved.

Limitations

A direct measure of walking economy was not included the present analysis, but total distance walked over a set period of time was reported. This is a primary aim of a larger parent study and will be reported in the future. Due to participants' schedules, illnesses, and availabilities, most did not complete the exercise protocol in 12 weeks, as originally proposed. Although the time of day that pre- and post- assessments were conducted was consistent, the corridor used for the 10WT was busier at some testing points than others due to changing class schedules of the spring, summer, and fall semesters. The corridor was blocked off down the middle to allow plenty of room for both students and research participants to move comfortably, but there was no way to control the amount of background noise. Performance did not appear to be much affected, although one participant waved to a passerby. The use of a long walkway to decrease the amount of turns during the 10 minutes was important, especially for individuals with PD.[51] Finally, because this was a pilot study, there was a small sample size (n=13).

Conclusion

The purpose of this pilot study was to investigate the effects of a performance-based training program on interlimb coordination for individuals with PD. There was no change of interlimb coordination between the lower limbs, but there was improvement observed of the arm – arm pair. Coordination between the contralateral arm – leg pairs were related to gait speed after completion of the training program, though this finding was only significant for the more affected arm and contralateral leg pair. Future studies should have a larger sample size to allow for more robust analyses, provide comparisons of overground, treadmill, and/or cuing based training programs to determine the responsiveness of coordination measures, and to investigate the retention of any change in coordination over time due to the progressive nature of PD.

APPENDIX I: REVIEW OF LITERATURE

At a glance, the act of walking seems relatively simple: one leg swings forward to step, followed shortly by the other leg performing the same swinging action. This relationship between the legs during walking is an example of interlimb coordination. Over the last few decades, interlimb coordination has received attention in the understanding of gait dynamics. Krasovsky and Levin (2010) define locomotor coordination as the "ability to maintain a context-dependent and phase-dependent cyclical relationship between different body segments or joints in both spatial and temporal domains".[4] The relationship of timing of the minimum and/or maximum The cyclical relationship described pertains to both upper and lower limb movements, pelvis, and trunk, all of which play a pivotal role to keep angular momentum minimal during ambulation.

Neuromuscular Coupling in Gait

Tight neuromechanical coupling of the lower extremities during bipedal gait is vital to achieve the goals of both support and progression.[36] Muscular contributions of the lower limbs provide both body support and progression of the trunk and leg.[52–56] During the double support, the trailing limb works to accelerate the body forward, while the leading limb resists this progression.[54] When speed is manipulated, the contributions from the hip, knee, and ankle flexor and extensor muscles may be altered in order to provide the adequate support and propulsive power needed.[55–57] This relationship between the supportive and propulsive actions, both interlimb and intralimb, provides a means of stability, and the ability to scale these forces in response to task or environmental demands.

Angular momentum about the center of mass (CoM) is highly regulated in all spatial movement directions (medial – lateral, anterior – posterior, vertical).[29] In fact, movement in the sagittal plane, mainly due to the swinging of the legs, is the largest contributor to the total body's angular momentum.[12] This momentum is balanced by the right leg producing angular momentum in the opposite direction of the left leg,[12,13,29] with almost complete cancellation during the swing phase, and the least cancellation during double support phase of the gait cycle. Accordingly, with an increase in speed, the time spent in double support decreases, and is correlated with increased cancellation.[12] The swinging motion of the legs, however, is not the only method of regulation. Elftman presented evidence, based upon calculation of each segment's contribution to angular momentum, that the swinging motion of the arms affect the body's rotation about the vertical axis and in the direction of progression to counter angular momentum produced by the legs and trunk, and is important to forward progression during gait.[14]Arm swing and the controlled upper body movements are vital to the smoothness of movement in walking.[58]

The majority of the body's total angular momentum, in all plans of movement, is generated by the arms and legs. During leg swing, positive work is needed to accelerate the leg forward, while negative work decelerates the leg to prepare for heel strike. When speed is increased, the work needed to accomplish the swinging of the leg, both positive and negative, is greater.[56] The percentage of angular momentum about the CoM generated by the lower limbs remains constant, a contribution of about 60%, while the arms provide around 25% at comfortable speeds, generating increasing amounts with increased speeds.[13] Suppressing arm swing in healthy adults, either by binding or holding arms to prevent swing, decreases gait speed[15] and step length[15,16], while increasing the vertical displacement of the CoM[16], the ground reaction moments[17], and the total body angular momentum as consequence from the loss of cancellation of angular momentum generated by the legs by the swinging of the arms.[12,17] These factors are thought to be related to the metabolic cost of walking, thereby influencing the economy of gait.[10,17,19]

Interlimb Coordination

The cyclical movement of both the arms and legs during locomotion allows the characterization of phase relationships. These relations can be out of (anti) phase, where the maxima of one limb occur near the point of the other's minima (180°), or in-phase, where the moments of limb maxima are close to simultaneous. As discussed above, angular momentum is kept low during gait by cancellation, especially in the transverse and sagittal planes by upper and lower body and the right and left leg swing, respectively,[12] emphasizing the importance of the coordinative relationships between limbs during ambulatory activities. In bipedal gait at normal and faster speeds, an out of phase relationship is expected for arm – arm, leg – leg, and ipsilateral arm – leg pairs.

Interlimb coordination can be measured by using the point estimate of relative phase (PERP; °).[10] The timing of each limb's maxima ($t_{limbx} and\ t_{limby}$) are used to determine their phase relationship (see equation 1). The stability of coordination between limb pairs is measured by the standard deviation of PERP (SD Φ). The Phase Coordination Index (PCI) builds upon PERP and incorporates accuracy and consistency of Φ. Accuracy and consistency are combined to yeild PCI, where a value of 0 describes exact and consistent anti-phase cyclical movement between contralateral limbs.[21]

Gait velocity, a control parameter of intralimb coordination, has been used to investigate motor control and different organismal constraints. The stability of the phase generation (Φ SD), is negatively correlated with gait speed, such that there is more variability present at lower velocities than at comfortable or faster velocities for all interlimb pairs.[10,59] These results provide evidence of both phase and frequency locking in interlimb coordination.[10] The coupling between legs shows the least amount of variability compared to arm-arm and arm-leg pairs, even at slower velocities.[10] As these examples show, rhythmic movement can be a change in spatial (amplitude), temporal (phase), or both aspects of coordination.[4] These spatial and temporal shifts can be the result of task, individual, or environmental constraints.

The manipulations of task and comparison of organismic constraints have been used to investigate motor control in the dynamics of gait, in particular, coordinative patterns and gait performance. Comparisons of different age groups,[21,43] neurological populations,[4,20,44,60] and task complexities[43,45] are represented in the present body of literature, and provide evidence for ability of coordinative measures to distinguish between groups and task conditions. A change in task, e.g., walking on a treadmill versus overground, can change coordinative movement patterns and spatiotemporal gait characteristics. To this end, older adults tend to walk with an increased cadence accompanied by a reduction in relative phase between arm-leg limb pair when asked to walk on a treadmill as compared to overground at matched speeds.[61] Mirelman et al. manipulated speed and task complexity during gait in young and healthy older adults groups. The participants were separated into age related groups in order to elucidate the role of aging in varying gait task demands on coordination between both the upper and lower extremities. Interlimb coordination between lower extremities in older adults was related to performance in balance and mobility tasks.[62]

Parkinson's Disease

Parkinson's Disease (PD) is a progressive neurological disorder that impacts mobility and ability to perform daily tasks. Deficient scaling and amplitude of movement, in both the upper and lower limbs, is observed in both upper body reaching tasks and gait.[63,64] The characterization of the changes in gait quality for individuals with PD has been well documented to date. Of note, there are gait parameters that are sensitive the effects of levodopa, a precursor to dopamine used in treatment of bradykinetic symptoms of PD. Stride length and arm swing velocity are sensitive to its effects, while temporal aspects of gait, such as swing and stride time duration, are resistant to its effects.[39] Even in the early stages of PD, decreased stride length is associated with postural instability.[65] Greater variability in double support time, even at matched speeds has been documented for mildly affected individuals during overground locomotion.[66] The resistance of the temporal parameters of stride time duration and variability is of particular interest because this is the period in which the least cancellation.[13]

There is characteristic asymmetric presentation component of symptoms in the milder to moderate stages of PD, which progress from unilateral to bilateral as the disease progresses. In one study, arm swing magnitude does not differ between those in the mild stage and controls, with comparable gait velocity, but the asymmetry of the magnitude is significantly increased in for those with PD,[67] although other studies show that the magnitude is lower for the same stage.[68] Reduction in arm and leg swing is associated with the degree of rigidity and bradykinesia.[46,68] Attentional strategies are used to explore the influence of arm swing on gait characteristics. When individuals with PD are instructed to deliberately swing their arms, arm swing amplitude increased as did gait speed and step length.[30] An arm swing cuing device, using haptic cues, has been created for individuals with PD. Visual and the device's haptic cues for arm swing resulted in increased step length during trails when either cue was present.[31]

Interlimb Coordination

Individuals with PD have poorer interlimb coordination between legs[5,20–22] and between arms,[20,23] even at the early stages of the disease. The asymmetric amplitude of arm and leg swing affects not only homologous limb pairs, but the coupling between the upper and lower extremities. Arm-leg coordination, both ipsilateral and contralateral pairs, has also been shown to be impaired,[2,3] with a correlation to poorer clinical scores of gait and posture.[2] Although speed influences the strength of interlimb coordination[24,25] and individuals with PD walk at slower speeds, evidence supports the notion that the reduction of coordination for individuals with PD is not due primarily to the characteristic slow gait.[20,30] **Figure 13** describes the interaction between the early motor sign of PD, reduced interlimb coordination (arm – arm & arm – leg pairs) leading to reduced cancellation of angular momentum about the CoM, which results in poorer gait performance. This broad conceptual framework was the motivation to investigate a performance-based intervention to improve interlimb coordination and gait.

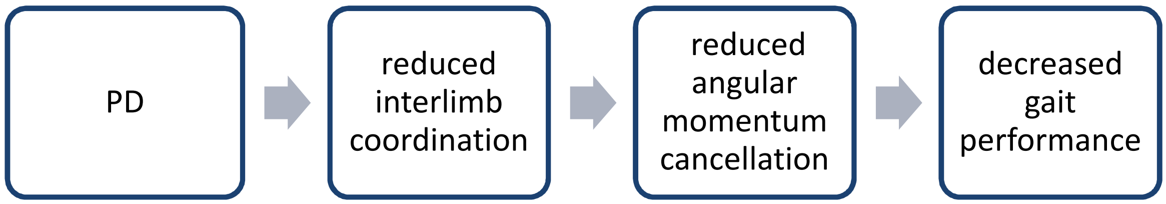

Figure 14 Reduced coordination impacts gait performance

Interlimb Coordination as an Outcome

A recent systematic review documents the lack of literature describing the effects of gait retraining on coordination. The majority of articles included described perturbations of speed, dual tasks, and direction.[32] Measures of coordination demonstrated moderate effect sizes, with the level of effect dependent on the population (i.e. stroke, PD, aging) and the specific measure used to quantify coordination. Thus, sensitivity of coordination can be dependent on methods of assessment. For example, in a comparison of individual's with PD and age matched adults (control), Nanhoe-Mahabier et al. found significant group and condition effects, treadmill versus overground, such that the control group walked at a faster speed in both conditions, but both groups had a faster preferred speed overground as compared to on the treadmill. A group difference in leg-leg coupling, as measured by PCI, was only found during the treadmill condition[3] , but the lack of difference could be due to the faster speed adapted overground and the relationship between slower gait speed and PCI.[24,43]

One of the few studies published with an intervention that measured coordination pre- and post-training was carried out by Schlenstedt et al. This study assessed changes to interlimb coordination, as a secondary outcome measured on a treadmill, after 8 weeks of balance or resistance training in individuals with PD targeting postural control. Interlimb coordination, as measured by PCI, did not change in a statistically significant way. It decreased in the resistance training group (p=0.061), but increased in the balance training group (p=0.286).[34] A small pilot study published in 2010 investigated the changes in PCI after robot assisted gait therapy in four individuals with PD and freezing of gait (FOG), and saw a reduction of PCI, measured overground, from a group mean of 9.0 to 7.8.[33] Neither of these studies investigated measurements of coordination between the arms or arm-leg coupling.

The importance of the arm-leg coupling, especially as it relates to gait performance, requires further research within the PD population. The intervention used to investigate this relationship in this study was a multimodal exercise training program that targets gait economy through moderate intensity exercises that utilized full body movements. The emphasis on full body movements included coordination of arm, leg, pelvis, and trunk movements. The characterization of interlimb coordination and gait performance after such an intervention will provide preliminary evidence to address this gap in the current literature.

APPENDIX II

Possabilities Training Sessions

Exercise Schedule: POSSabilities

Full Calendar			
Session	Direction	Focus	Emphasis
1	For	GI	Power
2	Rot	SS	Stepping
3	Back	GI	Stability
4	Lat	SS	Power
5	For	SS	Stepping
6	Rot	GI	Stability
7	Back	SS	Power
8	Lat	GI	Stepping
9	For	GI	Stability
10	Rot	SS	Power
11	Back	GI	Stepping
12	Lat	SS	Stability
13	For	SS	Power
14	Rot	GI	Stepping
15	Back	SS	Stability
16	Lat	GI	Power
17	For	GI	Stepping
18	Rot	SS	Stability
19	Back	GI	Power
20	Lat	SS	Stepping
21	For	SS	Stability
22	Rot	GI	Power
23	Back	SS	Stepping
24	Lat	GI	Stability

Abbreviations		
For=Forward	GI=Gait Initiation	PO=Power
Rot=Rotation	SS=Steady-state	SW=Swing
Back=Backwards		S=Stability
Lat=Lateral		

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings		
	Squats		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches		
	Walking backwards with single arm extension reach		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks		
	Walking split step with contralateral overhead reach		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Wall drill – hands on wall – push through floor – knees up		
	Staggered weight shift – 20 seconds each side (emphasize push-off with back leg)		
	Forward walking (pause in middle of each stride) (emphasize push-off)		
	Squat steps – non-alternating		
	Squat steps – alternating (switch sides every 3 repetitions)		
	Skater strides		
	Skater strides (3 normal – 3 short and quick – 3 normal – etc)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Forward walking (4 big steps – full stop – 4 normal steps – full stop) - repeat		
	Forward walking		
	Forward walking – pre-planned starts and stops – (use cones)		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 1 session 1 (forwards, gait initiation, power) Date:

Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines		
	Walking split step with trunk rotation – (rotate towards lead leg)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – open step 45° - return to even (weight shift)		
	Staggered – forward step with open 45° – return to staggered (weight shift)		
	Forward walking with non-alternating open 45° stepping (every 4th step)		
	Forward walking with alternating open 45° stepping (every 3rd step)		
	Forward walk to cone – stop – 360° march circle (emphasize hip rotation both legs) – finish walk - repeat with turn other direction		
	Y-drill - forward progression throughout		
	Fast forward walk full length – stop – 180° march circle (emphasize hip rotation both legs) – repeat (utilize turning in both directions)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Figure 8 drill – forward walk whole time		
	Box drill (with cones) – forward walking – (emphasize open stepping around corners)		
	Continuous forward walking laps with pre-planned speed changes (use cones)		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 1 session 2 (rotational, steady state, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings		
	Squats		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches		
	Walking backwards with single arm extension reach		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks		
	Walking split step with contralateral overhead reach		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – backwards step with high knee pause – staggered – return to even (20 sec each side)		
	Staggered – backwards step with high knee pause – staggered – return to staggered (20 sec each side)		
	Backwards stepping to even stance (non-alternating)		
	Backwards stepping to even stance (alternating)		
	3 steps forward – 3 steps backward (with pause on one leg in between)		
	3 steps forwards – 3 steps backward (with high knee pause on one leg in between)		
	Big backwards steps (5 steps – rest - repeat) non-alternating		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Big backwards steps (5 steps – rest - repeat) alternating		
	Backwards walking – forwards walking (shuttle drill with 4 cones)		
	V-drill (forwards and backwards walking)		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase 1 session 3 (backwards, gait initiation, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines		
	Walking split step with trunk rotation – (rotate towards lead leg)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – lateral step – return to even (push-off on return) (weight shift)		
	Even – lateral step – return to even (push-off and high knee on return) (weight shift)		
	Side stepping with push off		
	Side stepping with push off (band resistance)		
	2 side steps – forward walk (emphasize push-off on transition)		
	Side stepping (big steps)		
	Side stepping with gradual increases in step size (more and more push-off)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Box drill (use cones) (face same direction throughout)		
	3 backwards steps – 3 side steps (repeat other direction) (continuous)		
	Forward walking with preplanned speed changes (use cones)		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 1 session 4 (lateral, steady state, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings		
	Squats		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches		
	Walking backwards with single arm extension reach		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks		
	Walking split step with contralateral overhead reach		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered – high knee/dorsiflexion – staggered – return to staggered (20 sec each side)		
	Ankling (slow)		
	Calving (non-alternating)		
	Calving (alternating)		
	Calving with pre-planned speed changes (alternating) (use cones)		
	3 meters forward walk – 3 meters slow calving – 3 meters forward walk (use cones) (alternating)		
	Calving (as big as possible) (alternating)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Forward walking fly ins		
	Forward walking with sporadic band resistance (communicate with person verbally)		
	Forward walk with pre-planned speed changes (use cones)		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase 1 session 5 (forward, steady state, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines		
	Walking split step with trunk rotation – (rotate towards lead leg)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – open step 45° with pause – return to even (weight shift)		
	Even – high knee with pause – open step 90° – return to even (weight shift)		
	Even – open 45° step – even (non-alternating) (octagon)		
	Even – open 45° step – even (alternating) (band resisted)		
	Even – high knee with pause – slow open step 45° – fast walk 5 meters (repeat other direction)		
	Even – high knee with pause – slow open step ≥ 90° – fast walk 5 meters (repeat other direction)		
	Fast walk full length – stop – 180° march circle (emphasize hip rotation both legs) – fast walk return		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	W drill (walking forwards with turns) (use cones)		
	T drill (walking forwards with turns) (use cones)		
	Zig-zag cone course (forward walking with 45° turns)		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase1 session 6 (rotational, gait initiation, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings		
	Squats		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches		
	Walking backwards with single arm extension reach		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks		
	Walking split step with contralateral overhead reach		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	((Staggered – to even x2) (staggered – staggered x2)) - repeat other side		
	Backwards stepping (non-alternating) (push-off vs normal) (20 sec each side)		
	Backwards stepping (alternating) (push-off each step)		
	5 backwards steps – rest - repeat (alternating) (push-off each step) (band resisted)		
	5 big backwards steps – 5 normal backwards steps – repeat		
	5 fast backwards steps – 5 slow backwards steps - repeat		
	5 big backwards steps – rest – repeat (band resisted)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Backwards fly-ins (gradually increase speed)		
	Slow backwards walking 5 steps – fast backwards walking 5 steps – repeat continuously		
	V-drill (forward; up - backwards; down) (continuous)		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 1 session 7 (backwards, steady state, power) Date:

Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines		
	Walking split step with trunk rotation – (rotate towards lead leg)		
	Lateral Frankenstein's - (avoid trunk tilting) (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Lateral stepping (high knee both legs)		
	Lateral stepping triplets (band resistance around knees)		
	Lateral stepping triplets (band resistance around waist)		
	Lateral stepping triplets (high knee with lead leg)		
	Lateral stepping triplets (high knee with trail leg)		
	Lateral stepping triplets (high knee with both legs)		
	Forward walk 5 steps – full stop – 3 lateral steps (high knee both legs) – forward walk 5 steps – repeat		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Lateral walking with sporadic band resistance (trainer verbally communicates)		
	Forward walking with unplanned lateral triplets (trainer verbally communicates direction and timing of switch)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase 1 session 8 (lateral, gait initiation, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered weight shift (unplanned speed changes – trainer communicates)		
	Even – lift with pause – forward step – return to even		
	Forward walking (non-alternating pauses at mid-swing)		
	Forward walking (alternating pauses at mid-swing) (trainer randomly pushes side of hip to supply perturbation)		
	Forward walking (alternating pauses at mid-swing) (trainer randomly pushes side of hip to supply perturbation) (5 meters short/fast steps – 5 meters long/slow steps) (use cone)		
	3 forward normal steps – stop – 3 forward big steps – stop - repeat		
	Fast forward walking – stop - fast ankling (unplanned stopping with 1 sec pause) (band resistance around waist)(3 cones – 4 sections)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Forward walk full length with resistance on one side (stop 2 times) (dictate stops using cones)		
	Forward walking trainer walks behind and applies random lateral perturbations to shoulders and hips (jostling)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 2 session 9 (forwards, gait initiation, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – forward open 45 step – return to even (20 seconds each side)		
	Staggered – forward open 45 step - return to staggered (20 seconds each side)		
	Forward walking with non-alternating open 45 stepping (every 4th step) (band resistance)		
	Forward walking with alternating open 45 stepping (every 3rd step) (band resistance)		
	Walk to cone – stop – 360 open step/step over – finish walk-repeat with turn other direction (high knee both legs) (emphasize hip rotation)		
	V-drill (forwards) (stay outside cones) (band resistance from behind)		
	Fast walk full length – stop – 180 open step/step over with high knee hip rotation – fast walk return		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Figure 8 drill – forward walk whole time (band resistance on straight-a-ways) (mini band around ankles)		
	Box drill (with cones) – forward walking – stay outside cones – emphasize powerful open stepping around corners (mini band around ankles)		
	Continuous laps (4 cones around perimeter of training space) (slow on short edges, fast on long edges)		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 2 session 10 (rotational, steady state, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered – high knee – backwards step – return to staggered		
	Backwards stepping to even stance – non-alternating high knee (switch sides every 20 sec)		
	Backwards stepping to even stance – alternating high knee		
	Backwards walking with high knee (groups of 5 with 3 second pause in between) (band resistance)		
	Backwards walking with high knee (groups of 5) (trainer dictates step length changes between every group)		
	Backwards walking with big steps (groups of 5) (trainer randomly dictates start of each group)		
	Backwards walking with big steps (groups of 5) (trainer randomly dictates start of each group) (band resistance)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Backwards walk – stop – 10 high knees in place – backwards walk (divide room length into 3 pieces using 2 cones) (ask them to complete as fast as they can) (ankle band if needed)		
	Big backwards steps – 2 sec stop – big backwards steps (2 cones) (complete with biggest steps possible)		
	V drill (forward and backwards walking) (stay on outside of cones)		
			Total Steps:

GMU Rehabilitation Science POSSabilities - Phase 2 session 11 (backwards, gait initiation, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Lateral lunge weight shift (pause and hold with high knee on return)		
	Lateral ankling – (short and fast) – switch at cone – (long and slow)		
	Lateral calving – trainer stands close behind and applies random lateral perturbations to hips		
	Lateral band walk – band around proximal tibia – upright, crouched, lowest (dictate using 2 cones)		
	Lateral walking (very fast - very slow - very fast) – 2 cones to dictate speed change		
	Big lateral step x2 to forward walk 4 fast steps (facing one direction)		
	Lateral figure 8 (80% tempo) (switch at 20 seconds to ensure equal work on both directions)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Tennis ball partner catch lateral shuffle (2 cones) (3 meters) (toss directly to them)		
	Box drill with small obstacle step over (use half of figure 8) (switch at 20 seconds to ensure equal work on both sides)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 2 Session 12 (lateral, steady state, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	(long stride stance) Staggered – strong high knee with pause – staggered – return to staggered		
	Squat step – figure 8 – non-alternating (switch every 20 seconds)		
	Walking knee drive march (partner resisted) (drive into ground with each step)		
	High knee march (non -alternating) (band resistance from behind)		
	High knee march (alternating) (band above knee)		
	Partner resisted forward walk		
	Band resisted forward walking (heavy)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Walking fly ins (use cones)		
	Walking (continuous – longest strides possible)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 2 Session 13 (forward, steady state, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – open step 90 with pause – return to even (resistance band around hips) (movement away from resistance		
	Even – quick high knee with pause – open step (rotate as far as possible) – return to even		
	Even – right open step 45 – even – left open step 45 – even (resistance band around hips providing posterior resistance) (forward progression)		
	Even – high knee with pause – open 45 plus 5 forward steps (trainer dictates when to move after pause)		
	Zig zag obstacle course facilitating 45 degree turns (band resistance from behind) (open step with pause at each cone) (6 cones total)		
	Slow high knee march in place – random 5 fast steps in one direction (90 degree turn) (trainer dictates when to open step and walk and which direction they go)		
	Y-drill - Fast forward walk to vertex – stop – mini high knee march in place – trainer points to either top cone – participant walks to that cone - repeat		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Fast walk across room – stop – turn around as fast as possible – fast walk again		
	Forward walk to cone – stop – left open step 90 to cone (6 feet away) – stop – right open step 90 to other side of room		
	Stolen base walks – Trainer dictates randomly when to start (walk full length) (fast off the mark)		
			Total Steps:

GMU Rehabilitation Science POSSabilities - Phase 2 session 14 (rotational, gait initiation, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered to staggered backwards weight shift with 2 sec pause at mid-stance		
	Backwards walking to even (non-alternating) (switch sides every 20 sec)		
	Backwards walking to even (alternating)		
	Backwards walking with pause at mid-stance (3 sections, 2 cones) (fast-slow-fast)		
	Big steps backwards walking (3 sections, 2 cones) (without pause – with pause – without pause)		
	backwards walking zig-zag obstacle course facilitating 45 degree turns (pause on 1 leg at each cone)		
	Backwards walking with small fast steps – 3 fast forwards steps (trainer randomly dictates change)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Fast backwards walking figure 8		
	Continuous backwards walking (band resistance away from movement) (trainer randomly varies the resistance)		
	4 cones around perimeter of training space (backwards walking on short edges, forward walking on long edges) (comfortable pace)		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase 2 session 15 (backwards, steady state, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Lateral lunge (alternating)		
	3 lateral steps – change direction – 3 lateral steps (pause on outer leg during switch) (emphasize push off) (band resistance around ankles)		
	Lateral band walk triplets (slight bend in knees) (band below knee) (emphasize external rotation and abduction with both legs throughout)		
	5 quick lateral steps with no band resistance – 5 powerful long lateral steps with band resistance (trainer applies band resistance)		
	Forward walk with unplanned 3 quick lateral steps (trainer dictates direction and timing of steps) (aim for 2 sets per pass)		
	Diagonal stepping to even with band resistance (lots of resistance) (emphasize hard push-off on each step) (switch at 20 seconds)		
	3 diagonal steps to even – pause on one leg – 3 diagonal steps to even other direction (band around ankles)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Large lateral stepping (continuous, fast, band resistance around waist)		
	Tennis ball partner catch lateral shuffle (use 2 cones to set boundaries) (3 meters) (throw directly to them)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities – Phase 2 Session 16 (lateral, gait initiation, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up) (band resistance)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered weight shift (unplanned speed changes) (switch at 20 sec)		
	Even to staggered weight shift with leg cycle (band resistance from behind)		
	Forward walking with leg cycle (non-alternating) (band resistance from behind)		
	Forward walking with leg cycle (alternating) (unplanned speed changes)		
	Forward walking with leg cycle (alternating) (unplanned speed changes) (band resistance from behind)		
	Forward triplet (alternating) (unplanned step length changes)		
	Forward triplet with leg cycle (alternating) (unplanned starts)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Fast walk T-drill. Pause at each cone (stay inside cones)		
	Forward walking (comfortable pace)		
	Forward walking (unplanned starts/stops/speeds) "start fast", "start normal – go faster" "stop" etc		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 17 (forward, gait initiation, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – open step 45 – return to even (unplanned speed changes)		
	Staggered – open step 45 – staggered – return to staggered (pause in single leg stance) (unplanned step length changes)		
	Zig zag obstacle course facilitating 45 degree turns (open step with pause at each cone) (6 cones total)		
	Zig zag obstacle course facilitating 45 degree turns (unplanned speed changes) (6 cones total)		
	Zig zag obstacle course facilitating 45 degree turns (fast speed)		
	Figure 8 drill – normal speed – trainer applies random lateral perturbations to hips		
	Figure 8 drill – normal speed – trainer applies random lateral perturbation to hips and shoulders		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Figure 8 drill – forward walk whole time – unplanned speed and step length changes		
	Forward walking (trainer applies random lateral perturbation to hips and dictates unplanned starts and stops) (about 1 stop and start per pass)		
	Continuous laps around training perimeter. Trainer dictated speed changes		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 18 (rotational, steady state, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up) (band resistance)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered – staggered weight shift (band resistance from in front)		
	Staggered – staggered weight shift (big step length) (emphasize lunging deep into front leg and pushing back hard)		
	Backwards walking (non-alternating) (normal step – big step) (band resistance)		
	Backwards walking 5 steps – pause – 5 steps (emphasize push-off) (band resistance)		
	Backwards walking 5 steps – pause – 5 steps (big steps) (unplanned starting)		
	Backwards race starts (emphasize reaction time) (5 hard steps then normal backwards walk to other side)		
	Backwards walking with heavy band resistance (emphasize powerful steps)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Forward walk – stop – backwards walk (unplanned transition)		
	V drill (forward and backwards walking) (stay outside cones) (emphasize powerful transitions)		
	Forward walking comfortable pace		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 19 (backwards, gait initiation, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Lateral ankling (slow) (band around ankles)		
	Lateral step over calf (fast)		
	Lateral band walk – band around proximal tibia – upright, crouched, lowest (dictate using 2 cones)		
	3 steps forward – 3 steps lateral (right) – 3 steps forward – 3 steps lateral (left) – repeat		
	Fast forward walk with unplanned 3 quick lateral steps (trainer dictates direction and timing of steps) (aim for 2 sets per pass)		
	2 lateral steps (step over imaginary bar at thigh height) – 2 lateral steps (duck under low imaginary bar) - repeat		
	Lateral high knee stepping (band resistance around waist in opposite direction of movement)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Tennis ball partner catch lateral shuffle (emphasize speed) (2 cones) (6 meters) (toss directly to them)		
	Lateral walk box drill with small obstacle step over (use half of figure 8) (switch at 20 seconds to ensure equal work on both sides)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 20 (lateral, steady state, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: Block 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up) (band resistance)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: Block 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered – forward step with pause – staggered – return to staggered		
	Forward walking – non-alternating pause at midstance		
	Forward walking – alternating pause at midstance		
	Forward walking – alternating pause (trainer applies random lateral perturbations to hips)		
	Forward walking – alternating pause (trainer applies random lateral perturbations to hips and shoulders)		
	Fast walking (trainer dictates speed changes – very fast or very slow)		
	Fast walking (pause on one leg every 5^{th} step)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Fast figure 8 drill (pause on one leg at every turn)		
	Fast forward walking		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 21 (forward, steady state, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – open step 90 with pause – return to even (resistance band around hips) (movement away from resistance		
	Even – quick high knee with pause – open step (rotate as far as possible) – return to even		
	Even – right open big step 45 – even – left open big step 45 – even (heavy resistance band around hips providing posterior resistance) (forward progression)		
	Even – open 45 plus 5 forward steps (band resistance from behind) (band tension applied prior to movement) (emphasize push-off)		
	Zig zag obstacle course facilitating 45 degree turns (band resistance from behind) (emphasize open step and push-off around each corner) (6 cones total)		
	Zig zag obstacle course facilitating 45 degree turns (pause on one leg at each corner and emphasize large first step) (6 cones total)		
	Figure 8 (band resistance) (emphasize powerful open step at corners)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Fast continuous figure 8 (as many laps as possible)		
	Stolen base walks. Trainer dictates randomly when to start (walk full length) (fast off the mark)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 22 (rotational, gait initiation, power) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Marching in place with arm swings (gradually faster and larger movements)		
	Squats (slow down – fast up) (band resistance)		
	Single leg swing (hand on wall)		
	Back extensions (reach for ceiling)		
	Marching in place with snow angel arms (gradually faster and larger movements)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking marches (band resistance)		
	Walking backwards with single arm extension reach (gradually faster)		
	Walking with straight leg forward kicks (forward Frankenstein's)		
	Butt kicks (gradually faster)		
	Walking split step with contralateral overhead reach (deeper and bigger split step)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Staggered – high knee backwards step – staggered – return to staggered		
	Backwards ankling (band resistance from in front) (unplanned speed change)		
	Backwards ankling / calving / marching (unplanned transition in step height)		
	Backwards long steps (unplanned variable band resistance)		
	Backwards normal walking – 5 short quick steps (unplanned transition)		
	5 big backwards steps – stop – 5 fast high knees in place - repeat		
	Backwards fly ins		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Backwards V drill facing same direction throughout (high knees forward and backwards) (unplanned speed changes)		
	Backwards V drill facing same direction throughout (big steps on backwards – regular steps on forward)		
	Forward walk		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 23 (backwards, steady state, stepping) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

		(Y/N)	Notes:
Warm up: 1 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Trunk Rotations		
	Manual resisted isometric trunk rotation (apply smooth force)		
	Windmills		
	March circles - 90° turns – (emphasize hip rotation both legs)		
	Clock lunges (slow down, fast up)		
Warm up: 2 (5 min)	**Exercise: 20s on; 10s rest; (circuit x 2)**		
	Walking march with 45° turns on every 3rd step – (emphasize hip rotation on open step)		
	Grapevines (fast – slow - fast) (use cones)		
	Walking split step with trunk rotation – (rotate towards lead leg) (longer and deeper split step)		
	Lateral Frankenstein's - avoid trunk tilting – (1 leg down, other leg back)		
	Walking with sword pulls every 3rd step (fast – slow – fast) (use cones)		
Integration (21 min)	**Exercise: 40s on; 20s rest; (piecewise x 3)**		
	Even – lateral lunge weight shift – return to even (pause on return)		
	Lateral band walk – band around proximal tibia – upright, crouched, lowest (dictate using 2 cones)		
	Even – lateral lunge weight shift – return to even with high knee pause – 5 steps forward (initiate forward walk from single leg balance)		
	Slow forward walk – pause on one leg – 3 lateral steps (trainer randomly dictates pause)		
	Diagonal skater steps (big steps) (pause on each leg)		
	Diagonal skater steps (big steps) (no pause)		
	Box drill lateral stepping (band resistance around hips)		
Rehearsal (9 min)	**Exercise: 40s on; 20s rest (piecewise x 3)**		
	Tennis ball partner catch lateral shuffle (emphasize speed) (2 cones) (6 meters) (toss directly to them)		
	Fast forward walk with unplanned 3 quick lateral steps (trainer dictates direction and timing of steps) (aim for 2 sets per pass)		
	Forward walking		
			Total steps:

GMU Rehabilitation Science POSSabilities - Phase 3 Session 24 (lateral, gait initiation, stability) Date:
Subject ID: Total time: BP pre/post: ( ) ( ) HR pre/post: ( ) ( )

APPENDIX III

Coordination Variables by Section

Table 5 Arm-Arm and Leg-Leg by Section of 10WT
Average and standard deviation of the arm – arm (left) and leg – leg (right) coordination variables by section of the 10WT

Outcome	**Arm – Arm**		**Leg – Leg**	
	Pre	*Post*	*Pre*	*Post*
Φ 1	164.9 ± 12.4	168.1 ± 13.3	173.4 ± 18.6	170.1 ± 20.7
Φ 2	160.6 ± 7.7	168.3 ± 10.1	170.1 ± 18.4	169.3 ± 20.0
Φ 3	161.9 ± 9.1	168.9 ± 9.5	170.8 ± 18.6	168.8 ± 21.2
Φ 4	159.8 ± 9.7	167.0 ± 9.7	172.3 ± 15.8	168.5 ± 21.5
Φ SD 1	14.2 ± 6.7	12.5 ± 5.0	8.2 ±4.57	8.2 ± 5.3
Φ SD 2	15.5 ± 6.0	13.5 ± 5.4	9.0 ± 9.1	7.0 ± 4.7
Φ SD 3	12.9 ± 5.9	14.1 ± 5.0	9.9 ± 7.7	6.4 ± 3.3
Φ SD 4	17.4 ± 14.9	14.4 ± 4.9	7.2 ± 5.4	6.0 ± 4.4
PCI 1	10.0 ± 4.1	8.4 ± 5.2	5.6 ± 9.4	7.0 ± 10.6
PCI 2	10.9 ± 4.3	6.9 ± 5.2	6.6 ± 9.6	7.0 ± 10.5
PCI 3	10.1 ± 5.1	6.7 ± 4.7	5.9 ± 9.9	7.3 ± 11.2
PCI 4	11.4 ± 5.4	7.3 ± 5.39	5.5 ± 8.1	7.2 ± 11.4
Φ abs 1	17.9 ± 7.3	15.0 ± 9.4	10.0 ± 17.0	12.5 ± 19.1
Φ abs 2	19.4 ± 7.7	12.2 ± 9.4	11.8 ± 17.2	12.5 ± 18.9
Φ abs 3	18.1 ± 9.1	11.9 ± 8.4	10.6 ± 17.8	13.0 ± 20.1
Φ abs 4	20.2 ± 9.7	13.0 ± 9.7	9.7 ± 14.5	12.9 ± 20.6
Φ cv 1	0.086 ± 0.041	0.074 ± 0.029	0.050 ± 0.034	0.051 ± 0.039
Φ cv 2	0.097 ± 0.049	0.079 ± 0.028	0.055 ± 0.056	0.044 ± 0.037
Φ cv 3	0.081 ± 0.042	0.083 ± 0.027	0.060 ± 0.047	0.040 ± 0.025
Φ cv 4	0.11 ± 0.093	0.085 ± 0.027	0.045 ± 0.041	0.036 ± 0.026

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BIOGRAPHY

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