THE EFFECT OF A BIOMECHANICAL-BASED TAI CHI INTERVENTION PROGRAM ON POSTURAL STABILITY AND GAIT IN PEOPLE WITH PARKINSON'S DISEASE

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STATEMENT OF COVID-19 IMPACT

The COVID-19 pandemic greatly impacted the research and efforts of those that were involved in putting this thesis together. Initially, the thesis project was to be conducted as an in-person 12-week Tai Chi intervention that would be taught in a community centre for individuals with Parkinson's disease. Due to the global shutdown that occurred early January 2020, in-person gatherings were greatly restricted following the careful planning and advice by the Canadian government and health experts. This was unfortunate news. To protect the wellbeing of the research team and participants of the study, through deliberation and planning with my thesis supervisors and committee, we determined that it was best to shift the Tai Chi intervention program to online. Additionally, the in-person laboratory data collection portion of the project was delayed until September 2021 when resumption of office and laboratory work at the university was permitted (with restrictions). Thankfully, with the support of University of Ottawa, the university-offered ZOOM platform helped to enhance the enjoyment of the participants through our regular interactions and communication with them. From the period of November 2021 to April 2022, the participants met online together with the instructor and Tai Chi master, three days weekly, to learn to practice Tai Chi. This time was also used to unwind, de-stress, and encourage one another. All online 12-week Tai Chi and laboratory sessions concluded on April 8, 2022, the program itself was well-received by the participants.

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"If at first you don't succeed…try, try again."

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- NY, *Proverbs 3:5–6*

AUTHOR CONTRIBUTIONS

The results of the thesis are presented in five articles. The author contributions are stated as the following:

Article 1: *Biomechanics analysis of seven Tai Chi movements*. The supervisor (Dr. Jing Xian Li) conceptualized the study. The author (Nok-Yeung Law) carried out the data collection, statistical analysis, wrote and edited the manuscript. The supervisor (Dr. Jing Xian Li) participated in all aspects of the study and provided advice, content expertise, and reviewed the manuscript. Published in: *Sport Medicine and Health Science* (2022), March, 20, 1-68

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Article 5: *Effects of an online 12-week Tai Chi intervention on the electromyography activity of the lower limb muscles of individuals with Parkinson's disease during obstacle crossing*. The supervisor (Dr. Jing Xian Li) conceptualized the study. The author and supervisor (Dr. Jing Xian Li) contributed to the design of the study. The author (Nok-Yeung Law) carried out the data collection, statistical analysis, wrote and edited the manuscript. The supervisor (Dr. Jing Xian Li) participated in all aspects of the study and provided advice, content expertise, and reviewed the manuscript. Ready for submission.

ABSTRACT

Parkinson’s disease (PD) is a neurological condition that can lead to changes to gait and postural stability of people with this condition. Tai Chi (TC) has been recommended for the management of PD by improving muscle strength, balance, and coordination. However, biomechanics research in TC for PD is lacking. This thesis investigated the effects of a biomechanical-based TC intervention program for people in the early-stage of PD by realizing three specific research objectives: 1) to develop a biomechanical-based TC intervention program for PD; 2) to examine the effects of a 12-week TC intervention on gait and postural stability in people with PD, by pre-test and post-test biomechanical analysis of obstacle crossing; 3) to explore the neuromuscular effects of TC intervention on gait and postural stability by analyzing the electromyography (EMG) activity of the lower limb muscles during obstacle crossing.

Seven typical TC movements were selected, including Starting Form, Hero Touch Sky, Push Hand Back, Brush Knee and Twist Step, Repulse Monkey, Wave-hand in Cloud, and Lateral Forward Step to develop the TC intervention program. The joint angles, joint moment, and EMG signals of lower limbs muscles were analyzed during performance of the selected TC movements by an experienced TC master aged 38 years. Results showed that the selected TC movements are characterized by multidirectional movements, greater joint movement angles of the lower limb, and more active muscle activity than walking. The TC intervention program was formed based on the biomechanics analysis of the seven TC movements. The program consisted of 5–10 min warm up, 40 minutes of core activities, and 5 min cool down.

To examine the effects of a biomechanical-based TC intervention program on gait and postural stability and to explore the neuromuscular effects of TC intervention on the lower limb muscles in people with PD, fifteen individuals in the early stage of PD (*n* = 15, Hoehn and Yahr

stages 1 to 2; age 72.0 ± 6.9) participated in a 12-week online TC intervention, and 15 age- and sex-matched healthy participants ($n = 15$) served as control. The 3D motion data of the lower limb and EMG signals from the rectus femoris, adductor longus, tibialis anterior, semitendinosus, gluteus medius, tensor fasciae latae, and medial and lateral gastrocnemius muscles were collected during obstacle crossing from both groups using Vicon motion analysis system before intervention in both groups and after TC intervention in the TC group. Obstacle crossing was used to challenge the participants' gait and postural stability. Gait was assessed by measuring the temporospatial parameters such as crossing stride length, crossing step length, and crossing speed. Postural stability was assessed by measuring toe and clearance distance, pre- and post-horizontal distance, displacement and velocity of center of mass (COM), and COM-center of pressure (COP) separation. To examine the neuromuscular activity of the lower limbs following TC training, the ratio of the peak EMG, the integrated EMG (iEMG), and the ratio of the peak EMG and iEMG antagonistic pairs of the leading and trailing limb were examined during obstacle crossing and walking. In addition, the timed up-and-go test (TUG) and single-leg stance with eyes open and closed were tested. VICON Nexus, custom MATLAB scripts, and SPSS software (version 20) were used to analyze the data.

Analysis of the PD participants' obstacle crossing performance revealed that they had significantly slower gait speed, smaller hip flexion angles, and larger knee adduction angles of the trailing limb, significantly larger mediolateral (ML) COM displacement and COM-COP separation distance, and significantly higher peak EMG ratios of the adductor longus, gluteus medius, and tensor fasciae latae ($p < 0.05$) than the healthy participants. Following the 12-week TC intervention, the PD participants had significantly increased crossing stride length, significantly decreased ML COM-COP separation ($p < 0.05$) and significantly increased AP COM displacement ($p < 0.05$), and increased EMG activity of the tibialis anterior in the leading and trailing limbs during obstacle crossing, whereas the activity of the gluteus medius and adductor longus in the leading limb decreased ($p < 0.05$). Moreover, the significant differences in the EMG of the gluteus medius and tensor fasciae latae muscles between PD and healthy participants found in pre-test were no longer present. After the TC intervention, the PD participants significantly improved their performance on the TUG test ($p = 0.002$).

Therefore, people with early-stage PD presented changed gait and postural stability as well as changed neuromuscular activity of the lower limb. The 12-week online biomechanical-based TC intervention improved their gait and postural stability, particularly dynamic postural stability as measured by the COM-COP separation in people with early-stage PD. Compared to walking, performing the TC movements involved larger changes in the lower limb angles, range of motion, and higher muscle activity, particularly in the hip abductors and adductors. These characteristics of the TC movements could provide training to strengthen the muscles and improve the range of motion of the lower limbs. The gait and postural stability improvements following TC intervention are consistent with the neuromuscular activity changes in gluteus medius, tensor fasciae latae, and adductor longus muscles, indicating the mechanisms of TC training. The 12-week online biomechanical-based TC intervention program helped to decrease the ML COM-COP separation distance and could be used for the management of PD in the early stages of this condition.

PREFACE

The thesis includes five chapters. Chapter 1 introduces the background and research purpose of the thesis dissertation related to PD and key details related to reasons why gait and postural stability should be studied in this population. Chapter 2 reviewed the literature on postural and gait changes related to PD, highlighting the available exercises that have been used in past studies to manage the symptoms of PD. Chapter 3 provided the research design and methodology that was used. Chapter 4 presented the results of the study in the form of five research articles. Chapter 5 highlighted the key findings in the general discussion, outlined the concluding remarks for the conclusion and provided some important considerations for future studies.

DEFINITION OF TERMS

Balance: a state in which the body is in equilibrium (Ragnarsdóttir, 1996).

Base of support (BOS): the minimum area in which the body's in contact with the ground that includes the enclosed area surrounding the soles of the feet (or shoes) while standing or the support characteristics of both feet while walking (Lugade, Lin, & Chou, 2011; Meyer & Ayalon, 2006).

Center of mass (COM): a point equivalent to the total body mass in the global reference system that is the weighted average of COM of each body segment in 3-D space (Winter, 1995).

Center of gravity (COG): the vertical projection of COM onto the ground (Winter, 1995).

Center of pressure (COP): the vertical vector representing the "weighted-mean" of all the forces/pressures that is in contact with the ground (Hu, Zhao, Peng, Sun, & Qu, 2018).

Hoehn & Yahr (H&Y): a clinical rating scale defining the broad categories of motor function in Parkinson's disease (Bhidayasiri & Tarsy, 2012; Goetz et al., 2004). Stage 1 represents the minimal or no functional impairment, while stage 5 represents the highest stage of impairment.

Gait cycle: cyclical movement pattern used in human bipedal locomotion (Alamdari & Krovi, 2017).

Gait festination: the term festination is derived from the Latin word *festinare* which means *to hasten*, which has been used to describe the shortening of step length accompanied by increase in cadence (Nonnekes et al., 2019).

Gait freezing or freezing of gait (FOG): an episodic inability to generate effective stepping in people with PD. FOG is a transient episode, in which gait is halted and the subjects report that their feet are glued to the ground (Browner & Giladi, 2010).

Gait performance: refers to the assessment of a person's gait at their preferred-pace along a fixed (4 to 12 meter) distance along a walkway or pressure sensitive mat.

Mobility: the ability of a person to move around safely or be moved freely and easily in different conditions or environments (van der Kolk & King, 2013).

Montreal Cognitive Assessment (MoCA): is a brief screening tool for mild cognitive impairment (Nasreddine et al., 2005).

Motor modules: synchronously-activated group of skeletal muscles firing coincidentally to reduce complexity of motor control (Rodriguez, Roemmich, Cam, Fregly, & Hass, 2013).

Movement capacity: is the biomechanical capabilities and constraints that determine how humans move (Hills, Henning, Bryne, & Steele, 2003; Kuhn, Raichlen, & Clark, 2016).

Muscle co-activation: the simultaneous activation of the agonist and antagonist muscles (Frey-Law & Avin, 2013).

Muscle synergy: is the activation of a group of muscles for the purposes of achieving a wide range of movements (Horak, Henry, & Shumway-Cook, 1997; Ting & McKay, 2007; Wojtara, Alnajjar, Shimoda, & Kimura, 2014).

Neuromuscular function: is understood as the interaction of nerves and skeletal muscles that helps us to move (Robergs & Keteyian, 2003). This term is operationalized in terms of amplitude, onset timing, and time to peak muscle activity (Sherman, Glaviano, & Norte, 2021).

Posture: a combination of the relative positions of body segments or of the whole body with respect to a reference frame (Latash, 2012).

Postural control: involves the neural control of postural stability and postural equilibrium.

Postural stability: the body's ability to maintain balance by keeping its COM within the limits of its BOS. In steady state, *static postural stability* refers to the ability to maintain steadiness on a fixed, firm, and unmoving BOS (Goldie et al., 1989; Riemann et al., 1999). In a state of movement, *dynamic postural stability* refers to the ability to transfer the vertical projection of the COG around the supporting base (Goldie et al., 1989).

LIST OF ABBREVIATIONS

1-RM: one-repetition

3D: three-dimensional

6MWT: Six-Minute Walking Test

ANOVA: Analysis of Variance

AP: anteroposterior

BBS: Berg Balance Scale

BKTS: Brush Knee and Twist Step

BOS: Base of Support

COG: Center of Gravity

COM: Center of Mass

COP: Center of Pressure

EMG: Electromyography

ES: Erector Spinae

GM: Gluteus Medius

HC: healthy controls

H&Y: Hoehn & Yahr

iEMG: Integrated Electromyography

LFS: Lateral Forward Step

LG: Lateral Gastrocnemius

MCI: Mild Cognitive Impairment

MG: Medial Gastrocnemius

ML: mediolateral

MoCA: Montreal Cognitive Assessment

PA: Physical Activity

PD: Parkinson’s disease

PRE: Progressive Resistive Training

RF: Rectus Femoris

RM: Repulse Monkey

ROM: Range of Motion

SENIAM: Surface Electromyography for the Non-Invasive Assessment of Muscles

SLC: Single-leg stance test with eyes open closed

SLO: Single-leg stance test with eyes open

ST: Semitendinosus

TA: Tibialis Anterior

TC: Tai Chi

TFL: Tensor Fasciae Latae

TMT-B: Trail Making Test Part B

TUG: Timed-Up-and-Go

UPDRS-III: Unified Parkinson’s Disease Rating Scale- motor examination

WCST: Wisconsin Card Sorting Test

WHIC: Wave-hand in Cloud

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CHAPTER 1. INTRODUCTION

Parkinson's disease (PD) is a brain disorder that leads to uncontrollable movements such as shaking, stiffness, and difficulty with balance coordination (National Institute on Aging). The progression of this disease is categorized into five stages, stage 1 (the earliest stage) represents the minimal or no functional impairment, while stage 5 represents the highest stage of impairment (Bhidayasiri & Tarsy, 2012; Goetz et al., 2004). In stage 1 and 2, unilateral (affecting one side of body) and bilateral involvement without impairment of balance characterize these two early stages of the disease, respectively. Stage 3 is characterized by some postural instability, but the individual is still physically independent. In stage 4, the individual demonstrates severe disability but can walk or stand unassisted. In the highest stage, stage 5, the individual is wheelchair bound or bedridden (Source: Bhidayasiri & Tarsy 2012). Without treatment or medical intervention, the symptoms of PD can worsen over time and lead to loss of all brain functions and early death (Ananya, 2019). Individual with PD report bradykinesia (slowness in movement), stiffness in their muscles, and altered posture (Benatru, Vaugoyeau, & Azulay, 2008; Frenklach, Louie, Koop, & Bronte-Stewart, 2009; Horak, Dimitrova, & Nutt, 2005; Matinolli et al., 2007). Notably, this altered or "stooped" posture is characterized by an increasing narrow stance, forward tilting of the upper torso, rounding of the shoulders, and flexed knees and hip (Parkinson, 2002; Schoneburg, Mancini, Horak, & Nutt, 2013). Changes in the lower limb muscles were reported in this population that include weakness in the trunk and leg extensors muscles (Skinner, Christou, & Hass, 2019; Stevens-Lapsley, Kluger, & Schenkman, 2012) and increased muscle rigidity (Mak, Pang, & Mok, 2012; Mille et al., 2012; Wallén et al., 2015). Older adults with PD show increased antagonist co-activation of the upper and lower limb muscles that affects their posture and reactive balance (Arias, Espinosa, Robles-García, Cao, & Cudeiro, 2012; Lang, Hackney, Ting, & Lucas McKay, 2019; Rose, Løkkegaard, Sonne-Holm, & Jensen, 2013).

In the PD population, between 45% and 68% experienced at least one fall over a 12-month period, this percentage is higher (94%) among those with poor postural stability (Paul et al., 2014; Pelicioni, Menant, Latt, & Lord, 2019; Wood, Bilclough, Bowron, & Walker, 2002). Individuals with PD are more likely to fall compared to older adults that require hospitalization (Aminoff et al., 2011; Bouldin et al., 2013; Klein, Prokhorov, Miniovitz, Dobronevsky, & Rabey, 2009; Lamont, Morris, Menz, McGinley, & Brauer, 2017; Paul et al., 2017; Wielinski, Erickson-Davis, Wichmann, Walde-Douglas, & Parashos, 2005). Postural instability and changes in gait are problems that contribute to a higher rate of falls and injuries among those PD. The effects of PD can lead difficulties to complete a challenged locomotion, such as obstacle crossing due to changes in their gait and postural stability. To perform this task successfully requires good control of the movement in the trunk and legs, as well as the crossing height of the heel and toe. Several research studies have reported that people with PD walk with altered movement of their head and trunk as well as their steps during obstacle crossing (Cole, Silburn, Wood, Worringham, & Kerr, 2010; Cole, Sweeney, Conway, Blackmore, & Silburn, 2017; Jehu & Nantel, 2018; Pelicioni et al., 2018; Peterson & Horak, 2016). Disruption in the heads' movement can affect the control of the trunk's motion that alter posture and increase the risk falls (Menz, Lord, & Fitzpatrick, 2003), similarly the lack of control of the trunk's motion can disrupt the individuals' view while walking. This is one of the reasons leading to postural instability that is commonly observed among the PD population while walking or during performance of obstacle crossing (Galna, Murphy, & Morris, 2013; Pelicioni et al., 2018). It is therefore necessary to have a better understanding to the gait and posture during obstacle crossing to contribute to fall prevention in this population.

Obstacle crossing is a challenging task for those with PD to perform because it has higher demands to the movement capacity than walking and is difficulty for people with PD. It is a daily locomotion activity like walking and requires good dynamic stability, particularly in the mediolateral (ML) direction (Liu, Kuo, Wu, Chen, & Lu, 2018; Lord, Rogers, Howland, & Fitzpatrick, 1999; Maki & McIlroy, 2006). To successfully perform this task, individuals need to pay close attention on the movement of their leg and watch their steps as their lower limbs move across the obstacle. This task is challenging particularly for older adults who have greater difficulty avoiding obstacles due to poor vision and cognitive decline (Van Dieën, Pijnappels, & Bobbert, 2005; Galna, Peters, Murphy, & Morris, 2009). Evidence from fMRI studies suggest that individuals with PD demonstrate poor movement execution due to changes in their basal ganglia circuits in the (lower) brain that reduce cortical activation in the motor regions of the brain's cortex (Cameron et al., 2012; Rosenberg-Katz et al., 2013). In turn, individuals with PD have difficulties initiating different type of movements and performing cyclical movements such as walking because the functional connectivity between the brain and lower limbs is decreased. When demands of a task increase, this affects their cognition and the efficiency in which information from their surrounding environment is processed (Peterson et al., 2015; Salazar et al., 2017; de Souza Fortaleza et al., 2017). The reduce attention and cognitive decline makes it more difficult for people with PD to perform gait activities in a challenging environment or conditions that alter postural stability such as when avoiding or stepping over an obstacle (Stuart et al., 2018).

Biomechanics studies of obstacle crossing in healthy older adults report that the initial step before the obstacle is carefully controlled to reduce the risk of falls and to prevent contact with the obstacle (Muir, Haddad, Heijnen, & Rietdyk, 2015). Older adults slowed their gait speed and shortened their step length prior to crossing an obstacle whereas young adults do not (Muir, Haddad, van Emmerik, & Rietdyk, 2019). This indicate that older adults presented more conservative strategy such as using slower crossing speed, shorter step length, and shorter obstacle-heel strike distance compared to young adults during obstacle crossing (Chen, Ashton-Miller, Alexander, & Schultz, 1991). People with PD also demonstrate these changes but to a greater extent compared to older adults (Alcock, Galna, Hausdorff, Lord, & Rochester, 2018; Galna, Murphy, & Morris, 2010; Orcioli-Silva et al., 2017). These gait and postural changes are also more pronounce in the later stages of this disease (Vitório et al., 2014), and are more apparent when the surrounding environmental conditions are changed. Postural adjustments need to be made when avoiding an obstruction or hazard on the walking path. Consequently, during obstacle crossing performance, poor balance control, specifically increased ML sway of the body's center of mass (COM) have been reported in older adults with PD (Galna et al., 2013; Liu et al., 2018; Stegemöller et al., 2012). Our research group had used obstacle crossing test to examine gait and postural stability, including ML stability, in the healthy older adults (Li, Chang, & Li, 2018; Naghdlou, 2021). Combined with the published evidence from other research labs, the biomechanical analysis approach of obstacle crossing is well validated. Although some other tests such as turning has been used to examine dynamic postural stability, the biomechanical approach of obstacle crossing has been well established in our lab.

Single-leg standing (SLS) and Timed-Up-and-Go (TUG) are commonly used to examine movement capacity that is defined as the biomechanical capabilities and constraints that determine how humans move (Hills et al., 2003; Kuhn et al., 2016). SLS is a common test used to assess muscle strength in the lower limbs (Chomiak, Pereira, & Hu, 2015; Smithson, Morris, & Iansek, 1998). The SLS test can provide some indications to static postural stability. A weakness of SLS test is that it cannot reflect dynamic postural stability. The TUG is a simple test that is used to access mobility in the clinical setting. Several PD studies have used the TUG test to measure the changes in mobility following exercise or physical activity training (Demonceau et al., 2017; Leal et al., 2019; Silva-Batista et al., 2016, 2017; Wong-Yu & Mak, 2015). However, this time-based assessment of the participants' walking performance does not accurately capture or measure the changes in dynamic stability, particularly when postural stability is challenged. Dynamic postural stability is challenged during tasks such as walking and obstacle crossing when the body is moving. To study the dynamic postural stability changes due to PD, the strength of the lower limb muscles should be examined, as well as factors related to balance and coordination of the lower limbs' movement which determine the body's stability. Obstacle crossing is therefore an important task to evaluate the effects of PD on gait and postural stability, particularly this test can challenge gait and be used to evaluate the effectiveness of an exercise intervention program.

Exercise is recommended by professional bodies to help manage the symptoms related to PD (Michael J. Fox Foundation; Parkinson Canada, 2012a; Parkinson's Foundation). Evidence from a five-year follow-up study points to the role of regular exercise and physical activity in delaying the progression of the stage and motor symptoms of PD (Tsukita, Sakamaki-Tsukita, & Takahashi, 2022). Regular exercise can help to improve muscle strength, balance, and movement capacity (States, Sweeny, Rossi, Spierer, & Salem, 2017), as well as to maintain the cognitive processes for gait and postural stability (Cugusi et al., 2015; Lima, Scianni, & Rodrigues-de-Paula, 2013; Petzinger et al., 2013). People with PD are recommended to perform resistance (or strengthening) exercises, balance exercises, endurance training on a treadmill, and exercises such as stretching, Tai Chi (TC) or dancing (Parkinson Canada, 2012a). A minimum of 4 weeks of gait training and 8 weeks of balance training is required for the training effects to be maintained 3-12 months after completion of the intervention (Mak, Wong-Yu, Shen, & Chung, 2017).

The recommended exercises showed different training effects within the PD population. Resistance training improves muscle strength and mobility (Dibble, Hale, Marcus, Gerber, & LaStayo, 2009; Schilling et al., 2010), but not step length and gait velocity (Hass, Buckley, Pitsikoulis, & Barthelemy, 2012). Balance training improves postural balance and gait speed (Conradsson et al., 2015; Smania et al., 2010). Treadmill training increases stride (Schlick et al., 2015), but mobility and balance improved only with additional supportive devices or assistance from a trainer (Bello et al., 2013; Ganesan, Sathyaprabha, Gupta, & Pal, 2014). Each form of exercise appears to have their own unique training, focus, and impact. Consequently, although balance and resistance training are recommended for PD, the available exercises separately train balance or strength, respectively (Hulbert et al., 2019). Inconsistencies were noted for balance and resistance training; a few studies were unable to improve stride length, walking speed, or mobility (Carvalho et al., 2015; Conradsson et al., 2015; Demonceau et al., 2017; Hass et al., 2012; van den Heuvel et al., 2014; Morris, Iansek, & Kirkwood, 2009; Schlenstedt et al., 2015).

An appropriate exercise for PD would be one that is feasible and one that can be practiced with minimal supervision (Fasano, Canning, Hausdorff, Lord, & Rochester, 2017). Training should consist of “core ingredients” such as aspects of aerobic, balance, strength, and flexibility (Ellis & Rochester, 2018). Aerobic exercises or training are any activities that makes the heart beat faster or make breathing somewhat harder. Balance training refers to any forms of training that helps to improve postural control. Strength (or resistance training) is the use of resistance to muscular contraction to build strength, anaerobic endurance, and size of skeletal muscles. If fall prevention is the goal, a higher dose of exercises that challenge balance would be needed (Sherrington et al., 2008, 2017). A few high-intensity aerobic and resistance exercises (such as free-weights, bench, or leg press exercises) are effective to improve dynamic balance and mobility-related measures such as the Tinetti test and TUG, respectively (Demonceau et al., 2017; Leal et al., 2019; Silva-Batista et al., 2016, 2017). One resistance training study showed improvements in COP displacement during gait initiation after 2-day/week of training for 10 weeks (Hass et al., 2012). Resistance exercises can be challenging for those with PD due to the level of exertion and demands on the muscles during training. Different types of exercises require different length of program for the desire effect of the training to be gained. Muscle strength improved between 8 to 12 weeks of resistance training (Dibble, Foreman, Addison, Marcus, & Lastayo, 2015; S. S. Paul, Canning, Song, Fung, & Sherrington, 2014; Schilling et al., 2010; Silva-Batista et al., 2016), balance improved after 7 to 8 weeks of balance training (Landers, Hatlevig, Davis, Richards, & Rosenlof, 2016; Smania et al., 2010). Hence, the type and duration of the program should be considered to confer the full effect of exercise training (Ellis & Rochester, 2018; Mak et al., 2017; Ni, Hazzard, Signorile, & Luca, 2018).

TC is a popular form of exercise that has been practiced in China and around the world for many centuries. Both the *American* and *British Geriatric Societies* recommends TC to prevent falls in older adults (American Geriatrics Society & British Geriatrics Society, 2009). This recommendation is based on past research evidence that indicate practicing TC improves muscle strength, endurance, balance, proprioception, and neuromuscular function (Chang et al., 2016; Gatts & Woollacott, 2006; Gyllensten, Hui-Chan, & Tsang, 2010; Li, Xu, & Hong, 2009; Wang, Xu, & Li, 2017; Xu, Li, & Hong, 2006; Zhou et al., 2015). TC, a body-mind exercise, is suitable (Li et al., 2012; Parkinson Canada, 2012b) as well as safe and effective for the PD population (Huang & Liu, 2015; Li et al., 2012; Mak et al., 2017; Wong et al., 2009).

So far, eight published studies have examined the effects of TC training involving those with PD (Amano et al., 2013; Choi, Garber, Jun, Jin, Chung, & Kang, 2013; Gao et al., 2014; Kim, Jae,

& Jeong, 2014; Kim, Kim, Jae, & Son, 2011; Li et al., 2012; Vergara-Diaz et al., 2018; Zhang et al., 2015). These publications demonstrated that TC training can reduce the motor symptoms of PD [as measured by the Unified Parkinson's disease Rating Scale, sub-section motor (UPDRS-III)] and improve muscle strength, gait performance, balance, and mobility (Gao et al., 2014; Li et al., 2012; Vergara-Diaz et al., 2018; Zhang et al., 2015). However, the selection of the TC movements in the above-mentioned studies varies tremendously in terms of the number movements included and the styles involved. This may affect the training effects due to the biomechanical difference of the selected TC movements and styles. Moreover, the implemented TC programs did not indicate how the forms were selected or considered. Additionally, the TC effect on dynamic postural stability has not been examined in past TC training studies. In order to provide a more effective and feasible TC exercise program and understand the possible mechanisms of TC's effects for the PD population, it appears that a biomechanical analysis for the TC movements to be used in training is needed.

1.1 Problem Statement

Although the effects of exercises training have been previously examined, some research gaps remain: 1) the available exercises for PD people only emphasize training of one or two components (i.e., mobility, strength of the lower limb muscles) that are associated with movement capacity. TC training can train more than one component associated with gait and postural stability, such as muscle strength and neuromuscular activity of different muscle groups that contribute to postural stability in healthy old adults. However, its effects for PD people have yet to be fully explored; 2) in TC intervention studies for PD people, selection of the TC movements was not based on their biomechanical characteristics. To delay or prevent falls in PD, the selected movements should train gait and postural stability in both anteroposterior (AP) and mediolateral

(ML) directions by consideration of the TC movement kinematics, such as movement direction, angles and range of motion of the joint, kinetics, such as joint moments, and muscle activity of the lower limb; 3) a practical, home-based exercise program (i.e., an exercise intervention program that can be practiced in the comfort of inside or outside of the home setting) for PD is not available; 4) the effects of TC training on the lower limbs' neuromuscular functions during challenging locomotion are unknown. Neuromuscular function is understood as the interaction of nerves and skeletal muscles that helps us to move (Robergs & Keteyian, 2003). This term is operationalized in terms of amplitude, onset timing, and time to peak muscle activity (Sherman et al., 2021); and 5) clinical measures are the main evaluation approaches used in the studies examining exercise effects on gait and postural stability, which limit the understanding to dynamic postural stability. Therefore, the following research questions are raised:

1. What changes in gait and dynamic postural stability occur during obstacle crossing in people with early-stage PD? This data will help to form the baseline measure of the participants with PD, which can be compared to the healthy older adult (control) group and can be used to examine the pre- and post-intervention effects of TC training.
2. Which TC movements should be selected for the PD population to improve gait and postural stability, particularly dynamic postural stability in the AP and ML directions?
3. Can a biomechanical-based TC intervention program improve gait/postural stability for people with PD?
4. Whether the TC intervention can change neuromuscular function (in terms the amount of muscle activation, timing, and peak activity) of the lower limbs in people with PD.

1.2 Research Purpose

This study aimed to develop a biomechanical-based TC intervention program for people with PD and examine its effects on gait and postural stability through biomechanical analysis. The specific research objectives were:

1) To develop a biomechanical-based TC intervention program for people with PD by analyzing the biomechanical characteristics of TC movements;
2) To examine the effects of a 12-week TC intervention program on gait and postural stability in people with PD during obstacle crossing by analyzing their gait and posture during obstacle crossing at pre- and post-TC intervention tests;
3) To explore the neuromuscular training effects of TC intervention on the activity of the lower limb muscles by analyzing the EMG activity in the pre- and post-TC intervention tests during obstacle crossing.

1.3 Research Hypothesis

To meet the above objectives, we hypothesize the following:

1) The joint angles, joint moments, and muscle activity of the lower limbs would significantly differ between the selected TC movements and walking;
2) The PD and healthy older adult (HOA) groups would show significant differences in the following measures indicating gait and posture during obstacle crossing: a) gait speed, crossing length, pre- and post-horizontal distance, and toe–heel clearance distance; b) COM displacement and velocity and COM-COP separation distance; and c) maximum joint angles and range of motion (ROM) of the hip, knee, and ankle. Moreover, SLS and timed up and go (TUG) test scores would significantly differ between the two groups;

3) Among the participants with PD, the 12-week (3 days/week) biomechanical-based TC program would improve the following: gait during obstacle crossing as indicated by increased gait speed, step length, and toe–heel clearance distance during obstacle crossing; dynamic postural stability as indicated by altered COM velocity and displacement and COM-COP separation distance; and static postural stability as indicated by better scores on the single leg stance test (SLS) with eyes opened (EO) and closed (EC); and

4) Among the participants with PD, the 12-week TC intervention would lead to significant changes in muscle activity as indicated by the peak amplitude and integrated EMG (iEMG) values of the hip and ankle muscles such as hip abductor (tensor fasciae latae), dorsiflexor (tibialis anterior), and plantar flexor (medial and lateral gastrocnemius) muscles during obstacle crossing.

This research is innovative. First, a biomechanical-based balance and gait training program was developed (Article 2) for individuals with early-stage PD. Second, biomechanical analysis of the seven selected TC forms (Article 1) elucidated the mechanism underlying the benefits of TC on improving postural stability to provide scientific recommendations for people with PD. Furthermore, the analysis of changes in gait and postural stability during obstacle crossing helped advance the understanding of PD-related changes during challenging locomotion tasks and would contribute to the development of intervention programs to improve gait and postural stability (Article 3). Lastly, people with PD were trained with TC online for 12 weeks and were subjected to biomechanics analysis of gait and postural stability to elucidate the effects of TC training on gait, postural stability, and neuromuscular function in the PD population (Article 4 & 5). The findings would contribute to the management of PD through exercise intervention.

CHAPTER 2. LITERATURE REVIEW

PD is a neurological condition that restricts the ability to perform autonomous movements. The exact causes of PD are unknown, although genetic and environmental factors are linked to the etiology of this condition (Blauwendraat, Nalls, & Singleton, 2020; Elbaz et al., 2009; Lill, 2016; van der Mark et al., 2012). Dopamine, a neurotransmitter, is produced inside the substantial nigra region of the basal ganglia and aids in the control of voluntary movements. The basal ganglia are a group of subcortical structures connecting the higher brain centers to the body and body's segments (Clark, Boutros, & Mendez, 2017; Takakusaki, Saitoh, Harada, & Kashiwayanagi, 2004). When the dopamine level falls below 70%–80% normal levels, the symptoms of PD begin to appear (Bernheimer, Birkmayer, Hornykiewicz, Jellinger, & Seitelberger, 1973; Bezard et al., 2001). PD alters the functions of the basal ganglia and substantia nigra, thereby affecting the coordination and transmission of sensory information between the brain and limbs (Vaugoyeau & Azulay, 2010; Vaugoyeau, Hakam, & Azulay, 2011). Notably, the sequencing and timing of the upper and lower limb movements are changed during performance of different tasks (Huang et al., 2012; Kellaher, Baudendistel, Roemmich, Terza, & Hass, 2022; Roemmich et al., 2013; Vaugoyeau, Viallet, Mesure, & Massion, 2003). The main motor symptoms of PD include bradykinesia (slowness in movement), altered posture, increased muscle rigidity, loss of balance, resting tremors, and difficulty in performing everyday tasks, such as cooking and cleaning (Benatru et al., 2008; Frenklach et al., 2009; Horak et al., 2005; Jankovic et al., 2008; Matinolli et al., 2007). Notably, individuals with PD stand with a characteristic "stooped" posture that is characterized by a narrow stance, forward tilting of the upper torso, rounding of the shoulders, and flexed knees and hip (Parkinson, 2002; Schoneburg et al., 2013). These changes in their posture affect their ability to move freely, individuals with PD show reduced gait speed and stride length when they walk (Bohnen et al., 2013; Paul et al., 2014; Pistacchi, 2017; Winogrodzka, Wagenaar, Booij, & Wolters, 2005). These individuals are at a higher risk of falls and fall-related injuries (Bryant, Rintala, Hou, & Protas, 2015; Paul et al., 2014; Wood et al., 2002).

Although PD has no cure yet, exercise and regular physical activity can help reduce the symptoms and impact of the disease in terms of the individual's cardiorespiratory function, mood, and quality of life (Hou, Chen, Liu, Qiao, & Zhou, 2017; Schenkman et al., 2012; Uc et al., 2014). Recent evidence suggests that regular practice of mind–body exercises, such as TC, helps to improve gait and postural stability (Chan et al., 2005; Sungkarat, Boripuntakul, Chattipakorn, Watcharasaksilp, & Lord, 2017; Tao et al., 2017). In this literature review, topics related to postural stability, exercise, and TC will be covered with respect to PD. This review will present: 1) changes in gait and postural stability experienced by people with PD, 2) recommended available exercise programs for people with PD, and 3) effectiveness of TC training toward improving gait and postural stability among the PD population.

Parkinsonian gait is characterized by changes in temporospatial, kinematic, and kinetic patterns (Amboni et al., 2012; Horak, Nutt, & Nashner, 1992; Knutsson, 1972; Morris, Iansek, Matyas, & Summers, 1998; Schaafsma et al., 2003). The kinematic changes include a reduction in arm swing and trunk rotation, forward stooped posture, and a reduction in ground clearance distance (Martin, 1967). In the off-medication state (i.e., the period when their dopamine medication "wears off" or when Parkinson's symptoms come back and affect them the most), the temporal and spatial gait changes include slower gait speed and shorter stride length are reported in all stages of PD (Bohnen et al., 2013; Švehlík et al., 2009). Cadence is within the normal range regardless of the stage of the disease when compared with healthy controls (O'Sullivan et al., 1998;

Švehlík et al., 2009), except those with gait festination. The term **festination** is derived from the Latin word *festinare* which means *to hasten*, which has been used to describe the shortening of step length accompanied by increase in cadence (Nonnekes et al., 2019). Studies have characterized the consecutive footsteps of people with PD within a long or complex gait trial that becomes shorter and shorter with accompanying reduction in gait speed (Iansek, Huxham, & McGinley, 2006; Merello, Fantacone, & Balej, 2010; Nieuwboer et al., 2001). In the on-medication state, gait speed and stride length are reduced in people with PD compared with healthy controls (Almeida, Frank, Roy, Patla, & Jog, 2007; Hausdorff, Cudkowicz, Firtion, Wei, & Goldberger, 1998; Pistacchi, 2017; Sofuwa et al., 2005; Yang, Lee, Cheng, Lin, & Wang, 2008). Medication such as Levodopa would appear to help to maintain gait stability in PD, studies comparing the ON and OFF medication status in people with PD report that dopaminergic treatment reduces the variability in their step time, increase double support time and their stride length, thereby helping to maintain overall gait speed while walking (Ávila de Oliveira et al., 2021; Bryant et al., 2011). The limitations with dopaminergic treatments are they do not improve step asymmetry and arrhythmicity or walking performance when performing a dual-task that increase the cognitive load of the brain (McNeely, Duncan, & Earhart, 2012; Nantel & Bronte-Stewart, 2014). The administered treatment or intervention programs for PD needs to be compatible with the participant's medication status for an improvement in gait and postural stability to be observed.

2.1 Definition of postural stability

Postural stability refers to the body's ability to maintain balance by keeping its COM within the limits of its BOS (Goldie et al., 1989; Riemann et al., 1999). In a steady state**, static postural stability** refers to the ability to maintain steadiness on a fixed, firm, and unmoving base of support

(BOS) (Goldie et al., 1989; Riemann et al., 1999). The transfer or adjustment of the body's position depends on a series or group of muscles that are activated to move the body (Nashner & McCollum, 1985). In a state of movement, **dynamic postural stability** refers to the ability to transfer the vertical projection of the center of gravity (COG) around the supporting base (Goldie et al., 1989). This definition however is based on the dynamic movement of the COG that occurs around the BOS while standing, not during everyday movements such as walking or jogging; including the center of mass (COM) may add to the understanding of dynamic postural stability. According to Winter's study, the COM is a point representing the weighted average of the COM of each segment in 3D space (Winter, 1995). The COM may lie outside the limits BOS during performance of movements such as walking, not always within the BOS (Hof, Gazendam, & Sinke, 2005; Prince, Corriveau, Hébert, & Winter, 1997). Biomechanical studies have used motion analysis to examine dynamic postural stability. The center of pressure (COP) and/or COM have been examined during several types of movements performed by those with PD (Jehu & Nantel, 2018; Lu et al., 2021; Martin et al., 2002; Merello et al., 2010; Stegemöller et al., 2012).

2.2 Changes in kinematic and kinetic parameters that lead to altered gait performance

Gait performance typically involves the assessment of a participant's gait at their preferred-pace along fixed distance (4–12 m) along a walkway. A study by Sofuwa and colleagues examined 15 middle-stage (H&Y 2 to 3) PD participants who were in the on-medication state (Sofuwa et al., 2005). Meanwhile, another study examined 20 patients in early-to-late stages of PD (H&Y 1–4) who were in the off-medication state (Švehlík et al., 2009). Both studies reported that the overall ROM was reduced in all joints in the PD group; moreover, the hip extension values were lower, but the hip flexion values were comparable with those in the healthy control group. At the knee joint, participants with PD walked with increased mean knee flexion angle during single-support phase compared with the controls (i.e., healthy adults). The biggest difference occurred at the ankle joint. The ankle ROM during push-off was significantly reduced in the PD group by 19.8% compared with the controls. Both studies reported a reduction in plantarflexion at the ankle joints, but the difference was not significant compared with the controls (Švehlík et al., 2009). The changes in angles specifically in the hip and ankle suggest that the motor symptoms of PD have altered the activity of the surrounding muscles near these joint centers. These kinematic changes would negatively affect the functional mobility and gait performance in people with PD.

Differences in the kinetic data were more pronounced than those in the kinematic data. In the on-medication state, the maximum hip flexion moment at the hip joint was reduced by 25.9% in the PD compared with the control group (p = 0.03) (Sofuwa et al., 2005). Reduction (39%) of maximum hip power generated in stance phase (p = .001) and a reduction (32%) of maximum power absorbed in the stance phase (p = .03) was also observed (Sofuwa et al., 2005). At the knee joint, the maximum flexion and extension moment generation in stance phase did not significantly differ from that of controls (p = .301 and .952, respectively) (Sofuwa et al., 2005; Švehlík et al., 2009). A 43.7% reduction in the maximum knee power absorption (p = 0.009) also occurred in the late stance phase (50%–60% of the gait cycle) (Sofuwa et al., 2005). At the ankle, the maximal extensor moment was significantly lower at loading response (45%) and mid and terminal stance phases (15%) compared with the controls (Sofuwa et al., 2005). The ankle power generation was reduced by 28.2% (p = 0.0001) (Sofuwa et al., 2005). This reduction in ankle power and reliance on hip flexor power reflects an “accelerated aging process” when compared to unpaired older subjects (Morris, McGinley, Huxham, Collier, & Iansek, 1999). For older adults, hip flexor power was increased to compensate for the reduction in plantarflexor power due to weakness in the muscles of the ankle joint compared to young adults (Judge, Davis, & Ounpuu, 1996). The result of Judge et al. (1996) differed from the result of Sofuwa et al. (2005) who postulate that the normal compensatory strategies were not fully exploited in patients with PD. These changes suggest that gait dynamic and functional mobility is altered because of PD, individuals with PD demonstrated gait adaptations or compensation to maintain the ability to move but with limitations.

2.3 Changes in posture and postural stability

When maintaining an erected posture, postural stability refers to the body's ability to maintain balance by keeping its COM within the limits of its BOS (Goldie et al., 1989; Riemann et al., 1999). Postural stability can be classified as static or dynamic. *Static postural stability* is the ability to maintain balance while standing on a fixed, firm, unmoving surface, or BOS (Goldie et al., 1989; Riemann et al., 1999). *Dynamic postural stability* is the ability to transfer the vertical projection of the COG around the BOS as the body is shifting or moving (Goldie et al., 1989). Dynamic postural stability is altered when the COM shifts away or outside the BOS (Hof et al., 2005; Winter, 1995). Postural stability is influenced by vision, cognition, muscle strength, proprioception, and sensory-motor integration (Lord, Clark, & Webster, 1991; Lord, Ward, Williams, & Anstey, 1994; Paul et al., 2014); these factors may determine whether an injury will occur in the event of a fall. When standing still, people with PD can stand with a "stooped" posture that is characterized by an increasing narrow stance, forward tilting of the upper torso, rounding of the shoulders, and flexed knees and hip (Parkinson, 2002; Schoneburg et al., 2013).

Published studies have examined the effects of PD on static postural stability. Individuals with PD demonstrate poor control of their trunk's motion while standing and are more likely to lose their balance when performing clinical tests, such as single-leg stance or tandem stance tests

(Chomiak et al., 2015; Smithson et al., 1998). The lower single-leg stance time are related to a decrease in lower extremity muscular strength and endurance. The postural stability of people with PD are altered on the functional reach, sit-to-stand, and alternate step tests (Paul et al., 2013). During quiet standing, participants with the initial stages of PD (n = 10; H&Y 2.5-3) stand with increased ML postural sway of their COM and COP (Termoz et al., 2008). These changes are well documented in past studies (Chen et al., 2018; Ickenstein et al., 2012; Lu et al., 2021; Matinolli et al., 2007; Nantel, McDonald, & Bronte-Stewart, 2012). The findings of these studies revealed changes in the strength and endurance of the lower limb muscles due to PD. These changes along with an increase in the motor-related symptoms of PD would negatively affect static balance and make it more difficult for people with PD to control their trunks' movement.

Postural changes also occurred during gait (Iansek et al., 2006; Yang et al., 2008), obstacle crossing (Alcock, Galna, Perkins, Lord, & Rochester, 2018; Ambike, Penedo, Kulkarni, Santinelli, & Barbieri, 2021; Pieruccini-Faria, Jones, & Almeida, 2014; Simieli et al., 2017; Stegemöller et al., 2012), turning (Pillai, Shah, Glover, & Virmani, 2022; Song, Sigward, Fisher, & Salem, 2012), and gait initiation (Hass, Waddell, Fleming, Juncos, & Gregor, 2005). While initiating gait, participants with late-stage PD (H&Y $\geq$ 2.5) experienced a reduction in their COM–COP separation distance prior to the initial swing phase compared with those with the early stage of the disease (H&Y $\leq$ 2.0) (Hass et al., 2005). Hence, a conservative strategy may be adopted by the more severely affected patients to reduce the mechanical and postural challenge as well as the muscular strength requirements to successfully complete this task (Hass et al., 2005). When standing on a moving platform, AP and ML COM displacements increased among people with PD due to altered sensory and motor integration that is linked to poor postural control (Colnat-Coulbois et al., 2011; Horak et al., 2005; Jacobs & Horak, 2006; King & Horak, 2008). The peak heel and toe clearance distance were reduced during walking (Alcock, Galna, Lord, & Rochester, 2016; Alcock, Galna, Perkins, et al., 2018). These studies highlight that postural stability is reduced in people with PD. Postural stability may be further challenged during performance of more demanding tasks or conditions, such as obstacle crossing. Evidence shows that a shorter crossing stride length is correlated with the muscle strength of the hip flexors, hip extensors, knee flexors, knee extensors, and ankle dorsiflexors (Liao, Yang, Wu, & Wang, 2014). A better understanding of postural changes in PD can help to avoid falls and injuries.

Postural stability is altered during performance of obstacle crossing. Participants with early- to middle-stage PD (H&Y 1–3) demonstrated a 20% decline in the AP magnitude of the COM movement, a 36% increase in the ML magnitude of the COM movement, and a 21% decline in the resultant COM-COP separation across toe-off and heel strike compared with those in healthy adults (Stegemöller et al., 2012). As reported during level-ground walking, this reduction in AP COM motion and COM-COP separation distance due to poor muscle strength is referred as "cautious gait" strategy, which also occurs in older adults without PD (Hahn & Chou, 2004). When crossing an obstacle (height 10% of leg length), people with early- to middle-stage (H&Y 1-3) PD had no significant difference in lead and trail toe clearance distance compared with the controls, but they placed their lead foot closer to the obstacle after crossing (Galna et al., 2010). At higher obstacle height (knee height obstacle), participants with early- to middle-stage PD adjusted their leading and trailing toe clearance distance (when the toe was above the obstacle) accordingly to the height of the obstacle by shortening the crossing step, leading to reduced toe–obstacle and heel–obstacle distances (Ambike et al., 2021; Liu et al., 2018; Vitório, Pieruccini-Faria, Stella, Gobbi, & Gobbi, 2010). These adjustments to the position of their trunk and the placement of each step are necessary for individuals with PD to safely navigate over the obstacle.

2.4 Changes in neuromuscular function

PD alters neuromuscular function that led to postural instability and difficulty in performing voluntary movements. Reduction in dopamine production in the basal ganglia affects the connection between the higher brain centers of the body, in turn these changes alter the muscle activity of people with PD. Electromyography (EMG) analysis is used to identify differences between normal and abnormal muscle activity (Mills, 2005). The EMG signal produced by the muscle helps indicate the initiation of muscle activation, the relationship to force production, and the level of fatigue process occurring within the muscle (De Luca, 1997). Individuals with PD demonstrate altered motor recruitment and EMG activity (Rodriguez et al., 2013; Romanato et al., 2022). The effects of PD reduce cortical inhibition in the brain, this results in poor excitability of motor circuitry and a decrease in the rate of the development of EMG and force response (Praamstra, Plat, Meyer, & Horstink, 1999; Ridding, Rothwell, Inzelberg, & Rothwell, 1995; Tajitsu et al., 2022).

Participants with early- to middle-stage PD (H&Y 2-3) showed increased co-activation of agonist and antagonist muscles (Dietz et al., 1995; Keloth, Arjunan, Raghav, & Kumar, 2021; Powell, Joseph Threlkeld, Fang, Muthumani, & Xia, 2012), lower rates of force development associated with a decline in agonist muscle activation (Rose et al., 2013), and fewer motor module recruitment and modulation, indicating that their movements and movement patterns are less flexible and more rigid (Dietz et al., 1995; Morita, Kodaira, & Ikeda, 2014). Dimitrova and colleagues (2004) recorded the EMG activity of the muscle pairs surrounding the hip and ankle joints during testing under eight directional surface translation conditions. The results showed that participants with PD (H&Y stages 1 to 4) showed early antagonist onset and co-activation of agonist and antagonist muscles in their hip abductor–adductor and dorsiflexor–plantarflexor muscles in all eight directions of the perturbation. The change in the muscle activity could be attributed to their altered postural response patterns; in particular, the antagonist muscles was activated too early and was too large in magnitude in those with PD compared to healthy age-matched older adults, resulting in excessive muscle co-activation (Dimitrova, Horak, & Nutt, 2004). Past studies have examined the changes in muscle activities during everyday movement such as walking or under conditions that challenge postural stability when standing. Moreover, the proposed study aims to examine the muscle activity changes when performing a task that challenges dynamic stability. Following the past studies' techniques to analyze the EMG signals, by examining the signal's quality via EMG variables, such as amplitude, timing, and duration of muscle activation during challenging locomotion such as obstacle crossing, this would provide a deeper understanding into the neuromuscular effects of PD.

2.5 Importance of mediolateral stability for Parkinson's Disease

ML stability is important during dynamic and static conditions for prevention of falls. It is well-established that ML stability is strongly associated with fall risk (Brauer, Burns, & Galley, 2000; Hilliard et al., 2008), and that muscle strength is one of the most modifiable factors of postural control and a good predictor of falls (Billot, Simoneau, Van Hoecke, & Martin, 2010; Cattagni et al., 2014; Gafner et al., 2017; Muir, Berg, Chesworth, Klar, & Speechley, 2010). Older adults demonstrate less effective postural strategies and delayed or altered compensatory postural adjustments when the body is perturbed (Horak, 2006; Horak & Nashner, 1986; Maki, Edmondstone, & McIlroy, 2000; Mille, Johnson, Martinez, & Rogers, 2005; Singer, Prentice, & McIlroy, 2013, 2016). Weakness in their muscles surrounding hip joint area is one of the reasons for poor postural control. Older adults showed reduced hip abductor and adductor strength that are linked to lateral instability and falls (Chang, Mercer, Giuliani, & Sloane, 2005; Johnson, Mille, Martinez, Crombie, & Rogers, 2004; Kozinc, Smajla, & Šarabon, 2022). Whereas in young healthy adults, when their body is perturbed, they can adequately respond and make the necessary adjustments depending on the conditions (Kasahara & Saito, 2021). The loss of muscle strength and decreased muscle mass (Daley & Spinks, 2000; Goodpaster et al., 2006; Keller, Coldewey, & Engelhardt, 2014; Nilwik et al., 2013), coupled with increased postural sway (Laughton et al., 2003; Maki, Holliday, & Fernie, 1990; Du Pasquier et al., 2003), contribute to poorer balance while standing and performance of everyday activities by older adults. When performing a tandem stance that challenge postural stability, activity of the hip abductors is higher in older adults compared to young adults (Chang et al., 2005). This form of compensation is linked to weakness in the hip abductor and adductor muscles that help to regulate ML stability.

The ability to maintain ML stability is altered in both older adults and in people with PD. To study and to understand the amount of postural control that occurs in the ML direction, there are measures to track the postural changes or adjustments. Healthy subjects initiate gait by laterally shift their COG first followed by the forward shifting of their COG to generate enough forward propulsion (Rosin, Topka, & Dichgans, 1997). This change in the COG position causes the body to be temporarily unstable. To counter the forces of gravity and a large ML momentum that is exerted onto the body, the gluteus medius muscle activates to help maintain the body's COM within the BOS (Barak, Wagenaar, & Holt, 2006; Rogers & Evans, 1993). Older adults have weakness in the strength of their hip abductor and adductor muscles that is linked to lateral instability and falls (Chang et al., 2005; Johnson et al., 2004; Kozinc et al., 2022). For people with PD, there is also a severe decline in their extensors' strength when compared to those without

PD (Inkster, Eng, MacIntyre, Stoessl, & Jon Stoessl, 2003; Paasuke et al., 2004; Ramsey, Miszko, & Horvat, 2004). During quiet standing, although a similar postural control mechanism is used as older adults, individuals with PD stand with a stooped posture and maintain their balance by using a “mixed” ankle and hip strategy (Termoz et al., 2008).

ML stability is worse in people with PD than older adults, especially during demanding conditions that pose a challenge to their postural stability. Measures such as the COM-COP separation distance represent the scalar distance at a given time between the COP and COM, specifically how well the COM is maintained within the BOS by moving the COP back and forth around the COM (Corriveau et al., 2001). Individuals with PD have difficulty maintaining good balance and postural stability when avoiding or crossing over an obstacle. Individuals with PD showed a smaller AP COM-COP separation distance during obstacle crossing compared to older adults (Galna et al., 2013; Stegemöller et al., 2012). This cautious approach allows dynamic stability to be maintained at the cost of the speed in which the task is performed. Despite using a smaller COM-COP separation distance, individuals with PD were more dynamically unstable than the healthy older adults (Stegemöller et al., 2012). A smaller separation distance allows the individual to compensate for weakness in their hip muscles. The findings are consistent with gait initiation studies involving those with PD. Participants with H&Y scores of 2.5 or higher demonstrated a smaller resultant COM-COP separation distance than individuals with no known neurological problems or those with H&Y scores of 2.0 or less (Hass et al., 2005; Martin et al., 2002). Examining the COM and COP relationships during tasks such as tandem stance, gait initiation, or obstacle crossing can help to understand the compensation or postural changes when postural stability is challenged or altered. Postural stability measures such as the COM or COP could be used to evaluate the effectiveness of a treatment or intervention programs.

2.6 Available Exercise Programs for Parkinson's Disease

2.6.1 Neuromuscular Effects of Exercise

Exercise training helps to optimize the muscle activity and EMG patterns in people with PD (Bailey et al., 2018; Volpe et al., 2020). The EMG patterns and onset/offset timing of the lower leg muscles improved during gait performance in people with early-stage PD (H&Y 2.5) after undergoing 3 weeks (30 minutes, 7 days weekly) of home-based gait training (Thaut et al., 1996). In a group of patients with H&Y stages 1–4 PD, 15 times of 1.5-hour tango sessions for 3 weeks reduced the antagonist onset time, duration, and magnitude during the postural response test while standing on a moving platform (McKay, Ting, & Hackney, 2016). Exercise training can improve the EMG amplitude and increase the number of recruited motor modules; this finding suggests that a group of coactive muscles can help produce more reliable motor output by the muscles (Allen, McKay, Sawers, Hackney, & Ting, 2017; Hubble, Naughton, Silburn, & Cole, 2018). Hence, EMG analysis can be used to study the mechanism of exercise training, specifically the strategy of using training to optimize the activation and patterns of muscles. Analysis of the EMG activity of antagonist and agonist muscles, particularly the changes in amplitude, duration, and onset/offset (timing) of the EMG signal, can help indicate whether a neuromuscular change has occurred post-exercise training.

In animal model, regular exercise and physical activity provide both a neuroprotective and neurorestorative effect on the brain by increasing the production of good neurotrophic factors within the neurons (Lau, Patki, Das-Panja, Le, & Ahmad, 2011; Zigmond & Smeyne, 2014). Long-term changes inside the brain following exercise training helps to improve communication between different areas of the brain that are important for balance, coordination, and control of voluntary movement. Regular physical activity on a treadmill help to improve the movement capacity of induced Parkinson's rats by deterring the loss of dopamine producing neuronal cells in the brain (Hou et al., 2017; Lau, Patki, Das-Panja, Le, & Ahmad, 2011; Yoon et al., 2007). However, these findings have yet to be reproduced in humans. Regular physical activity minimizes the risk of falls among this population by strengthening the lower limb muscles, reducing the muscle rigidity, and improving posture (van der Kolk & King, 2013; Rosenthal & Dorsey, 2013). The following sections will review the four commonly used types of exercise training for PD: resistive training, balance training, endurance training, and multimodal training in addition to the literature on high-intensity interval training and tai chi training.

2.6.2 Resistance Training

Resistance training programs are effective toward improvements of strength and balance. Studies on resistance training mainly involved participants with H&Y stages 1 to 3 PD. The duration of resistance training programs ranged from 7 weeks (Schlenstedt et al., 2015) to 24 months (Corcos et al., 2013; Rafferty et al., 2017). The forms of resistance training included were training on an eccentric ergometer (Dibble et al., 2009), performing compound movements (e.g., squats, toe/calf raises) with body/cuff or free weights (Leal et al., 2019; Schlenstedt et al., 2015), and progressive resistance exercise (PRE) (Rafferty et al., 2017; Silva-Batista et al., 2018; Vieira-Yano et al., 2021). Although there are some discrepancies between research groups, in general, the level of resistance was set at 70–80% of the participant's one-repetition maximum (1-RM). Paul and colleagues (2014) asked their participants to perform the first set at 50% of their 1-RM, the second set at 50% of their 1-RM, and third set at 60% of their 1-RM (Paul et al., 2014). Once the participants were able to perform 10 repetitions in the third set and were able to maintain good form and speed of movement, the 1-RM was increased by 5% and progressed accordingly.

Whereas in other studies, the resistance was set at 70-80% of the participants' 1-RM and each participant performed 2 sets of 12 repetition (Corcos et al., 2013; Rafferty et al., 2017). Some variations in the number (or different combinations) of sets and repetitions maximum were noted in other studies (Silva-Batista et al., 2018; Vieira-Yano et al., 2021). Resistance training performed three times weekly for 12 weeks significantly improved the single-leg standing time (p = 0.002) (Strand et al., 2021). Other studies reported improved performance on a leg press machine after 8 weeks (2 days weekly) of lower limb training (Schilling et al., 2010). Similar improvements in leg extensor, knee and hip flexor, and hip abductor strength were reported in another study after 7 weeks of training (Paul et al., 2014). However, resistance training alone cannot improve the gait velocity and step length among people with PD. Meanwhile, three studies that used low-volume or adapted resistance training showed significant changes in speed and/or stride length (Dibble et al., 2009; Leal et al., 2019; Vieira-Yano et al., 2021). Other studies showed either a non-significant or no improvement (Hass et al., 2012; Schlenstedt et al., 2015). Significant improvements were reported on the TUG test after resistance training (Dibble et al., 2009; Leal et al., 2019; Schlenstedt et al., 2015; Silva-Batista et al., 2016).

In summary, resistance training can improve the lower extremity strength and mobility (as measured by the TUG test), but the effect depends on the type of resistance training selected as well as the length, frequency, and intensity of the training. In literature, the strength of the lower limb muscles can improve at 7–8 weeks after resistance training. Mobility can improve after whole-body exercises, which cannot be obtained from training only the lower limb muscles due to factors related to dynamic stability and balance. About 3–6 months of resistance training can significantly improve gait speed and stride length. One study showed an improvement in mobility after combined resistance and balance training (Silva-Batista et al., 2016). Most of the reviewed studies on resistance training have focused on the improvement of muscle strength and mobility but did not consider aspects of balance, postural stability, or gait. The impact of resistance training on balance has not been explored yet with biomechanical or clinical outcomes [such as the Berg Balance Scale (BBS)] and should be considered for the PD population. Other approaches (such as the biomechanical analysis of a person's gait) could be used to assess balance capacity post-resistance training among individuals with PD.

2.6.3 Balance Training

Studies on balance training revealed that the risk of falls disproportionately affects the PD population compared with their healthy counterparts. In the reviewed studies, the participants were in distinct stages of PD: five studies involved participants in H&Y stages 2–3, one study in 1.5–4 (Landers et al., 2016), and another in 3–4 (Smania et al., 2010). Training was typically conducted 2–3 days weekly, with 45–60 minutes per session. The duration of the interventions was 4–12 weeks. This type of balance training involves the destabilization of the COM and the coordination training of the arms and leg (Smania et al., 2010). It also includes the use of additional external cues, such as visual feedback (Atterbury & Welman, 2017; van den Heuvel et al., 2014; Landers et al., 2016), practice inside or outside the home (Ashburn et al., 2007; Atterbury & Welman, 2017; Shen & Mak, 2014), or use of single- and/or dual-tasks (Conradsson et al., 2015) or computerized systems or devices (Shen, Wong-Yu, & Mak, 2016). Balance training can improve gait velocity (Conradsson et al., 2015; Landers et al., 2016; Shen & Mak, 2014, 2015) and balance (as measured by the BBS) (Landers et al., 2016; Smania et al., 2010) as well as TUG (Wong-Yu & Mak, 2015). However, changes in muscle strength have not been evaluated or documented in previous studies.

The aspects of gait, mobility, and balance are improved after balance training. Improvements in stride length and gait velocity are important for people with PD because of the limitations with step asymmetry and arrhythmicity during walking that are not improved with dopaminergic treatments (McNeely et al., 2012; Nantel & Bronte-Stewart, 2014). Of the 11 reviewed studies, 10 were randomized control trials. The differences and inconsistency in the outcome measures could be due to the complexity and variations in the forms and duration of the training programs. The effects of training indoor against outdoor settings and the participants' daily habits and lifestyles are future considerations but may add to the complexity of the intervention program. The reviewed studies trained their participants for only 2 days or a few hours weekly, whereas 3 days weekly of training would provide better training outcomes (Landers, Navalta, Murtishaw, Kinney, & Pirio Richardson, 2019; Smania et al., 2010). Balance training should be considered because the literature has identified its importance toward improving outcomes related to balance and mobility (Judge, 2003; van der Kolk & King, 2013; Sarasso et al., 2022).

2.6.4 Endurance Training – on Treadmill

Endurance training, such as treadmill training, is recommended for people with PD (Parkinson Canada, 2012a). Studies employed treadmill training for participants with PD in H&Y stages 1–3 or 2–3, whereas few studies evaluated those with PD at stages 1–4 (Harro et al., 2014; Schenkman et al., 2012; Schlick et al., 2015). Training was conducted for 30 min, 2–3 days weekly. The intervention length was 4–20 weeks. The participants were trained at high-intensity or 65%–80% of their heart rate reserve (Bridgewater & Sharpe, 1996; Schenkman et al., 2012; Shulman et al., 2013). Modifications included treadmill's speed and/or introduction of visual cues (Cakit, Saracoglu, Genc, Erdem, & Inan, 2007; Schlick et al., 2015). The motor symptom of PD (UPDRS-III) remained steady (slightly increased) after high-intensity treadmill training for 4 days weekly for 6 months (Schenkman et al., 2018). Treadmill training led to improvements in the stride length after 5 weeks with or without visual cues (Schlick et al., 2015). A similar finding was reported in the treadmill group of another study that used auditory cues (Bello et al., 2013). Significant improvements in BBS were reported after 4 weeks of partial body-weight support treadmill training (Ganesan et al., 2014). The effect was inconclusive for gait speed and dependent on the pace of the treadmill belt and presence of visual or auditory cues during training (Cakit et al., 2007; Harro et al., 2014; Schlick et al., 2015). Improvements in the TUG test were not significant after treadmill training with or without visual or auditory cues (Bello et al., 2013; Schlick et al., 2015).

Endurance training can improve gait performance, balance, and mobility. All programs adopted a standard training length of 30 minutes. The severity of PD did not affect the outcome measures after the training. However, modifications in performance speed and addition of visual cues while training affected the outcome measures. Interestingly, 5–6 weeks of treadmill training program are sufficient to improve stride length and gait speed, although the reviewed studies suggested that improvements in balance and mobility are dependent on the addition or presence of visual cues and/or weight-supported devices.

2.6.5 Multimodal Training

Multimodal training refers to the use of three or more combined exercise modalities, including aerobic, strength, balance, coordination, and/or flexibility training, to improve physical capacity (F. Li et al., 2018; Mak et al., 2017). The trained participants with PD were in H&Y stages 1–3 (Capato 2020; Lander 2019) and 2–3 (Ellis et al., 2005; Pelosin et al., 2020). The intervention sessions were typically 45–60 min, 2–3 days weekly; and the intervention length was about 5–8 weeks. The duration of the intervention and the frequency (days weekly) of training were not consistent with the above-mentioned studies (Frazzitta et al., 2015; Landers et al., 2019; Zhang et al., 2015). Multimodal training involves treadmill training, upper/lower body exercises, and single-leg stance training (Landers et al., 2019). Additionally, training can include strengthening the core muscles, obstacle crossing, cycling, and standing on an ankle correction board (Zhang et al., 2015). Based on the reviewed studies, the performance in the six-minute walk test (6MWT) significantly improved (Ellis et al., 2005; Frazzitta et al., 2015; Schenkman et al., 2012), two studies showed significant improvements in stride length and/or gait velocity (Rafferty et al., 2017; Zhang et al., 2015). Eight weeks of intensive (4 days weekly) multimodal exercise training improved the balance (Mini-BESTest), strength (sit-to-stand test), endurance (as measured by the 6MWT), and to lower the scores on UPDRS-III (Landers et al., 2019). Multimodal exercises training may thus help improve one or more aspects of physical capacity.

Several weaknesses have been noted in multimodal training programs for PD. First, the exercise forms selected are inconsistent, that is, they address only one or two components of physical capacity; this would not qualify as multimodal training, although it is stated as such in the papers (Capato, Nonnekes, et al., 2020; Pelosin et al., 2020; Penko, Barkley, Rosenfeldt, & Alberts, 2019). A standard or consistent multimodal program that could be followed has not been established yet. Second, high-intensity training or long-period of multimodal training is a requirement to obtain an effect (Frazzitta et al., 2015; Landers et al., 2019; Rafferty et al., 2017). Motor-related symptoms were reduced, and the mobility improved after 4 weeks (5 days weekly) of training; improvements were also noted in balance and strength after 8 weeks (3–4 days weekly) and temporospatial parameters after 12 weeks (2 days weekly). Third, multimodal training can be very costly. The cost to deliver a 24-week (2days weekly) multimodal program for older adults aged 70 years or above (n = 224) is $223 849 USD (or $1004 per person) (F. Li et al., 2018). Further research is needed to examine the feasibility and cost-effectiveness of multimodal training for the PD population. Despite the potential benefits of multimodal training, factors such as the intensity and frequency of training need to be adjusted to better meet the individuals' capacity limits (Baker, Atlantis, & Fiatarone Singh, 2007; Capato, de Vries, et al., 2020; Goodwin, Richards, Taylor, Taylor, & Campbell, 2008; Orcioli-Silva et al., 2014).

2.6.6 High-Intensity Interval training

High-intensity interval training (HIIT) is a popular interval training exercise for athletes and healthy adult populations (Karlsen, Aamot, Haykowsky, & Rognmo, 2017; Laursen & Jenkins, 2002). The HIIT program has been applied to the clinical population such as those with heart failure (Freyssin et al., 2012; Wisløff et al., 2007), coronary heart disease (Moholdt et al., 2009; Rognmo, Hetland, Helgerud, Hoff, & Slørdahl, 2004), and heart transplant recipients (Dall et al., 2014). HIIT can help to improve insulin sensitivity, blood pressure, and body composition among adults with overweight and obesity classification (Campbell et al., 2019). Peak oxygen consumption (VO_2 peak), a strong independent predictor of mortality, is shown to increase following HIIT (Keteyian et al., 2008; Ross, Porter, & Durstine, 2016; Vanhees, Fagard, Thijs, Staessen, & Amery, 1994). This type of training is determined to be safe for patients with coronary artery disease or heart failure (Wewege, Ahn, Yu, Liou, & Keech, 2018). The terminology used to describe HIIT unfortunately varies between different research groups (Karlsen et al., 2017; Wisløff, Ellingsen, & Kemi, 2009; Zhou, Zhao, Guo, Wang, & Wang, 2022). Typically, HIIT is performed in activities that involve large muscle groups (such as brisk uphill walking, running, or cycling) at peak heart rate (HR_{peak}: 85–95%) or VO_2 peak (80%–90%) for 4 mins, followed by a period of recovery or rest at lower intensity (HR_{peak}: 60–70%) for 2–3 mins (Karlsen et al., 2017). A typical HIIT session consists of 4×4 min interval but can also be performed as 4×5 min, 3×5 min, 5×3 min, or something similar (Karlsen et al., 2017).

The effects of HIIT have recently been examined in people with PD; three publications were reviewed, namely the effects of HIIT on cognitive function (Fiorelli et al., 2019; Harvey et al., 2019), inflammation levels (Malczynska-Sims, Chalimoniuk, Wronski, Marusiak, & Sulek, 2022), and heart rate (Harvey et al., 2019). The sample sizes in the three reviewed studies were small and statistical inference of their findings was limited. It was reported that HIIT training led to a significant decrease in tumor necrosis factor-alpha (TNF-α) and increase in anti-inflammatory cytokines such as iterlukin-10 (IL-10) ($p < 0.01$) (Malczynska-Sims et al., 2022). Typically, the HIIT program was 12-weeks, 3 days per week for 45 to 60 minutes with a HR_{peak} of 80% (Malczynska-Sims et al., 2022). This training intensity of this study was lower than the recommended HR_{peak} of 85–95% (Karlsen et al., 2017), it is unknown whether individuals with PD can maintain this high activity level. In another study, participants with early-stage PD (H&Y 1 to 2) were recruited for a 36-week high-intensity treadmill training. The participants' adherence rate to the prescribed 80–85% HR_{peak} during training was 80.2%, 3.2 day/week (Schenkman et al., 2018). This study was not classified as HIIT because no "interval training" component was included. Other limitations were noted in the reviewed studies. Fiorelli and colleagues' (2019) classification of "high-intensity" was based on the participant's perceived exertion, rather than objective measures such as their VO_2 peak or HR_{peak}. Different form of exercises (such as cycling or resistance training) were included (Fiorelli et al., 2019; Harvey et al., 2019; Malczynska-Sims et al., 2022), it is unclear if these forms of training would lower the demands or alter the scope of the HIIT program. By including a sensorimotor agility training component, this would benefit gait and postural stability; more work is needed to determine if these type of modifications to the HIIT program are suitable or effective for this population.

The evidence from the reviewed studies suggests that HIIT training would be a more suitable exercise for those with cardiovascular-related diseases than PD and for improvement on outcomes related to cardiorespiratory functions. There is limited evidence to support the beneficial effects or the direct impact of HIIT on balance and dynamic stability for PD. The biomechanical changes in balance, gait, and postural stability following HIIT has yet to be explored in participants with PD. In the reviewed studies that examined the effects of HIIT for PD, the design of these study were not randomized control trials; their study's sample size was small, and their training program do not adhere to HIIT description or design. Several publications have used "high-intensity" resistance or aerobic training studies involving participants with PD (re: the previous sections *2.6.2 Resistance Training* and *2.6.4 Endurance Training*), but without the *interval* training component in their HIIT design. It remains unclear if these "high-intensity" resistance and aerobic training have similar benefits as HIIT programs. Future studies needed to consider whether, cycling and resistance training forms of HITT training, are suitable for people with PD. More work is needed to determine whether HIIT can improve gait and postural stability in people with PD.

2.6.7 Tai Chi Research

There is strong research evidence to indicate that practicing TC can help to improve muscle strength, endurance, balance, proprioception, and neuromuscular function (Chang et al., 2016; Gatts & Woollacott, 2006; Gyllensten et al., 2010; Li et al., 2009; Wang et al., 2017; Xu et al., 2006; Zhou et al., 2015). Past studies have examined the biomechanical characteristics of TC movements. Kinematic analysis of TC movements demonstrates that compared with walking, TC movements present a significantly larger three-dimensional (3D) movement in the forward, backward, and sideway directions, a significantly larger ROM of the joint of the lower limbs (Law & Li, 2014; Mao, Hong, & Li, 2004; Wu, Liu, Hitt, & Millon, 2004), and longer double-limb support times (Law & Li, 2014; Mao et al., 2004). A kinetic study of TC stepping has shown that compared with walking, TC stepping has significantly smaller peak compressive forces, larger peak shear forces in the ankle, knee and hip joints, and larger peak moments in the knee and hip joints (Wu & Millon, 2008). Larger hip abduction and extension moments have been reported during the performance of two TC movements, the Repulse Monkey and Wave-hand in Clouds compared with the hip joint abduction and extension moments of walking (Li & Law, 2018). The results reveal that TC differs from the joint-moment patterns of walking, the peak moment generation time is much longer during TC performance, and the joint moments are active across an entire gait cycle. Thus, TC could be a safe and effective training for the elderly.

Muscle activity during TC performance has also been explored. The earliest study, published in 2003, examined the muscle activity of the trunk and lower limb during push-hand movement and Brush Knee and Twist Step using EMG analysis (Chan, Luk, & Hong, 2003; Xu, Li, & Hong, 2003). Push-hand movement generates high muscle activity in the lumbar erector spinae and the rectus femoris with concentric and eccentric contractions occurring in muscles of the lower limbs (Chan et al., 2003). During the performance of Brush Knee and Twist Step and TC stepping, the activation of the lower limb muscles is slow and coordinated, this activity level is higher than during walking (Wu et al., 2004; Xu et al., 2003). In 2007, an EMG study revealed that the TC activation level of knee muscles is higher than during walking (Tseng, Liu, Finley, & McQuade, 2007). Nevertheless, muscle activity during TC is poorly understood despite the growing interest and popularity of TC (Hackney & Wolf, 2014). Moreover, an integrative and synchronized study on kinematics, kinetics, and muscle activity during TC is lacking, which limits the understanding of the biomechanics of TC movements.

TC has been applied to manage the symptoms of PD because of its unique effects on improving muscle strength and balance. Studies showed that TC training can lead to good spatial awareness, neuromuscular reaction, and strength of the lower limbs (Gyllensten et al., 2010; Wang et al., 2017; Xu et al., 2006). A 16-week TC training program was found to be effective toward improving the knee flexor strength in older adults aged 60 years and above (Li et al., 2009). Thus far, only a few studies examined the effect of TC training on people with PD; as such, the scientific understanding of the effect of TC on this population is limited. In this section, a review of literature will be presented on the effect of TC on muscle strength, balance, and gait performance. Table 7.1 in the *Appendix* highlights the key findings from the eight reviewed studies.

The reviewed studies indicated that a 12-form simplified TC training (3 days weekly) for 12 weeks improved the AP and ML displacement of the COP during gait initiation suggesting improved dynamic postural control that would help move the body forward through subsequent steps and to maintain ML stability, respectively (Kim et al., 2011). Training that involved teaching 6–8 TC forms for (2 days/week) for 24 weeks improved the UPDRS-III scores and TUG performance (Li et al., 2012; Vergara-Diaz et al., 2018). The intervention also improved the knee extensor and flexor strength during dynamometer testing as well as the gait velocity, stride length, and TUG performance (Li et al., 2012). The UPDRS-III scores were reduced after a 10-form TC with home-based training for 12 weeks (once weekly), but not for TUG or 6WMT (Choi, Garber, Jun, Jin, Chung, & Kang, 2013). The UPDRS-III scores, BBS, step length, and AP/ML COP displacement during gait initiation did not change after 16 weeks (2 days weekly) of training that involved the first eight (i.e., Commencing, Part the Wild Horse's Mane, White Crane, Brush Knee and Step Forward, Playing the Lute, Reverse Reeling Forearm, Left Grasp Sparrow's Tail, Right Grasp Sparrow's Tail) movements of a 24-form (Simplified) Yang-style TC (Amano et al., 2013). A 24-form Yang-style TC training (3 days weekly) for 12 weeks improved the BBS but did not significantly improve the UPDRS-III scores or TUG performance (Gao et al., 2014). However, the same TC training (with the same intensity/duration) improved the AP/ML of the COP during gait initiation (Kim et al., 2014). The same TC training (*2 days weekly*) for 12 weeks improved the gait velocity but not the stride length, UPDRS-III, or BBS (Zhang et al., 2015). A six-form TC training (2 days weekly) for 24 weeks did not improve the UPDRS-III, TUG, and gait velocity (Vergara-Diaz et al., 2018).

In summary, TC training improves balance and muscle strength and reduces the motor-related symptoms of PD. However, the effectiveness of TC toward TUG and 6MWT measures has limitations that would otherwise reflect changes in mobility and movement capacity. TC training for 12 weeks can increase the stride length, depending on the selected TC styles/forms and intensity of training. Biomechanical measures were not used and would add to the understanding of the effect of TC training on people with PD. Several weaknesses were noted: 1) previous studies did not examine dynamic postural stability post-TC training; 2) the selection of TC forms was not based on the biomechanical evidence that is available to show that TC specifically provides training to lateral postural stability, which is important for fall prevention; and 3) research on the body–mind effects of TC was not conducted yet.

2.7 Summary

PD limits the ability to move due to changes in balance, cognition, and neuromuscular activity. Regular physical activity and exercise can help improve the movement capacity in people with PD. Resistive training, balance training, endurance training, and multimodal training are the popular forms of exercise for this population. Despite their popularity, each form of exercise can only improve one or two aspects of postural stability, namely, balance, strength, and proprioception. Moreover, TC is a recommended for people with PD because it helps improve muscle strength, balance, and coordination. To structure a short, feasible, and practical TC program for the elderly, the selection of TC forms is critical because the movement characteristics are some of the factors influencing the training effects. Thus, selecting the TC movements should be based on the biomechanical study of TC movement that would help in developing a feasible, practical, and effective TC program. TC is similar to rhythmic exercise such as tango or dance that trains the participant’s foot placement, whole-body coordination and awareness, and attention to theirs and their partner’s movements (Hackney & McKee, 2014). Although TC shares many similarities to rhythmic programs, such as tango or dance, their relationships and mechanisms are not identical. TC training influences movement capacity and could help slow down the progression of PD. Several positive effects are clinically documented, but the uniqueness of TC training has not been fully explored using biomechanical approaches. This endeavor would further enhance the understanding of PD and offer a potential way to better manage this condition.

CHAPTER 3. METHODOLOGY

3.1 Study design

The study included three sub-studies. Study 1 developed a biomechanical-based TC intervention program for people with PD. Study 2 used a pre- and post-intervention design to examine the effects of an online 12-week TC program on gait and postural stability in people with PD. Study 3 explored the neuromuscular effects of TC intervention on gait and postural stability in people with PD. From the collected data from study 2, the EMG activity of the lower limb muscles during obstacle crossing in the PD participants who accepted TC training were analyzed. Figure 1.1 (*below*) illustrates the study design. Details of the number of participants involved and measures that were collected in each study are highlighted in the diagram.

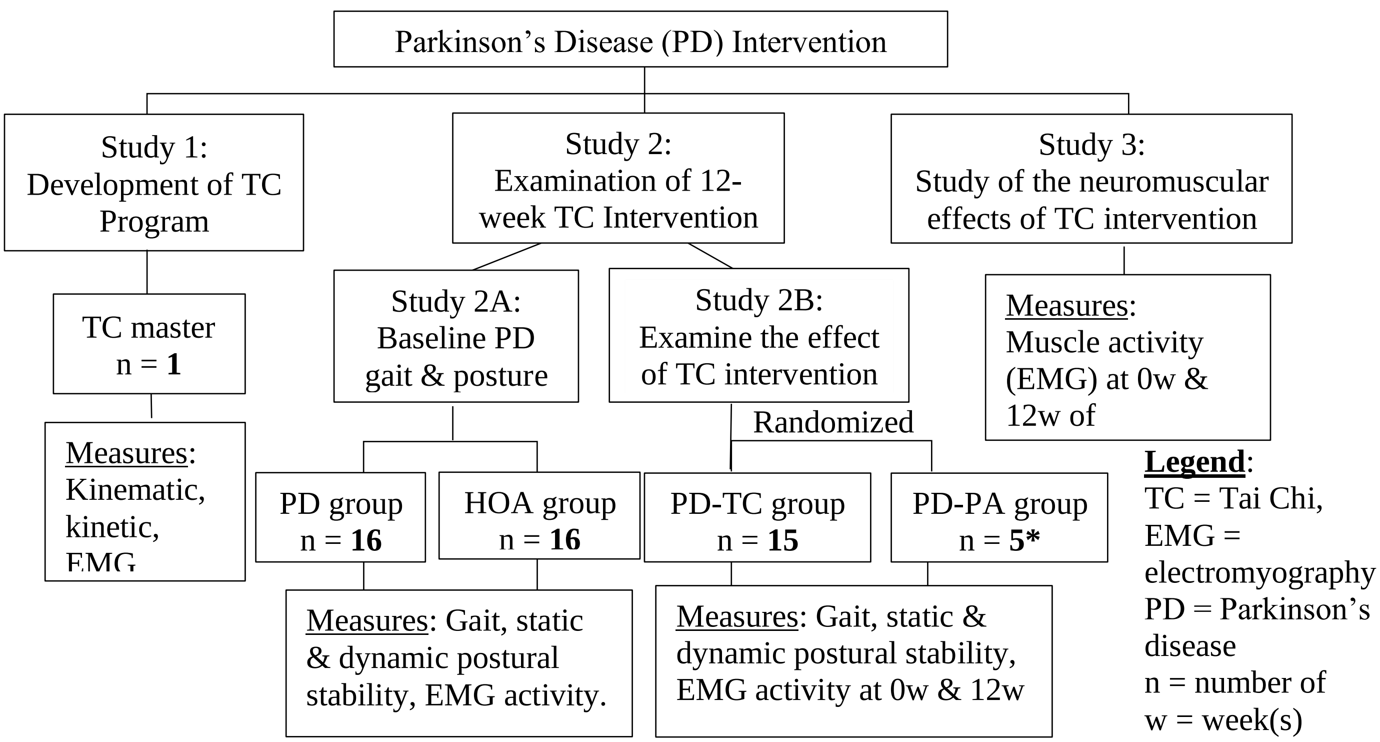

Figure 1.1. The study design for a 12-week intervention program for PD. *Due COVID-19 pandemic only five participants' data were collected for the PD-PA group. HOA: healthy older adult, EMG: electromyography, PA: physical activity.

3.2 Participants

Experienced TC master

For study 1, to develop a biomechanical-based TC intervention program for PD, one TC master (*n* = 1; age, 38 years old; body weight, 84.2 kg; height, 176.5 cm) with more than four years of Wu style TC experience was recruited.

PD group

The participants for study 2 and 3, community-based adults with early-stage PD (H&Y stage 1 to 2), between the ages of 65 to 80 years, were recruited. This group consisted of 16 individuals (9 males and 7 females). They had an average length of PD for 7.0 ± 5.4 years. Recruitment of the participants was conducted through: (1) referrals from local medical clinics (i.e., physician/neurologist offices); and (2) local support groups associated with *Parkinson's Canada*. The participants were excluded if they had impaired mobility, dementia, cardiovascular disease, poorly controlled hypertension, or if they were currently on medications known to impair balance.

Healthy older adult (HOA) group

Community-based adults that were age sex-matched HOA were recruited. This group consisted of 16 individuals (9 males and 7 females). The members of this group were recruited through: (1) referrals from local medical clinics (i.e., physician/neurologist offices); and (2) care partners or family members of the individual who attended the *Parkinson's Canada* support group. The same exclusion criteria as the PD group were followed.

PD-TC group

The same participants from the PD group were recruited. In total, of the 17 recruited participants with PD, 15 completed the pre- and post-intervention TC program (15/17, 88%

completion). Reasons for discontinuing was one participant had unrelated back pain before starting the program and one participant moved away (from Ottawa).

PD-Physical Activity (PA) group

The PA group were asked to track their level of PA over 12 weeks. This group was required to engage in at least 60 min of regular PA on their own for three times weekly. Regular PA included walking, cleaning, performing chores inside the home, and/or climbing the stairs. No restriction was made to limit others forms of PA. Individuals in the PA group were permitted to engage in organized sports and instructor-led class such as boxing and dance to ensure that the participant recruitment process is feasible. An active control group was used for comparisons between the groups who will or will not receive formal TC training and to reflect the daily lifestyle and activities of a typical individual with PD from the community. Similar to the TC training group, the participants in this group were asked to complete an activity log form for monitoring, and this form will be collected weekly to monitor their regular PA levels. **Due to reasons related to COVID-19 pandemic, only five participants were able to complete 12-week PA intervention** (data in *Appendix* section). Without a PA group, a limitation is that the improvements in the TC group cannot be associated purely with the effects of TC training alone.

3.3 Instrumentation & Measurements

Force plates & walkway

The ground reaction forces were recorded using four force plates at 2000 Hz (models 9286AA, Kistler Instruments Corporation, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA) embedded in the middle of an 8 m-long walkway. The force plates are fastened to a metal track which is fixed to the concrete floor and built into the walkway.

Only approximately 3 m of the walkway was used in the calibration of the testing volume used for data collection. The concrete floor of the walkway is covered with a rubber material to provide for a cushioning effect.

Motion analysis system

The temporospatial and kinematic data was obtained from Vicon Motion Analysis System. 10 infrared tracking cameras (two Vicon Vantage cameras (model v5) and eight Vicon Vero cameras (model v1.3); Oxford Metrics, Oxford, UK) was used to capture the TC movements and walking trials at 200 Hz. All cameras hanged from the ceiling or mounted on individual tripods that were placed around the testing area (Figure 1.2 *below*). The cameras are arranged so that all the reflective markers on the subjects can be detected during data collection. All cameras are synchronized to capture and generate the 3-D movements of interest.

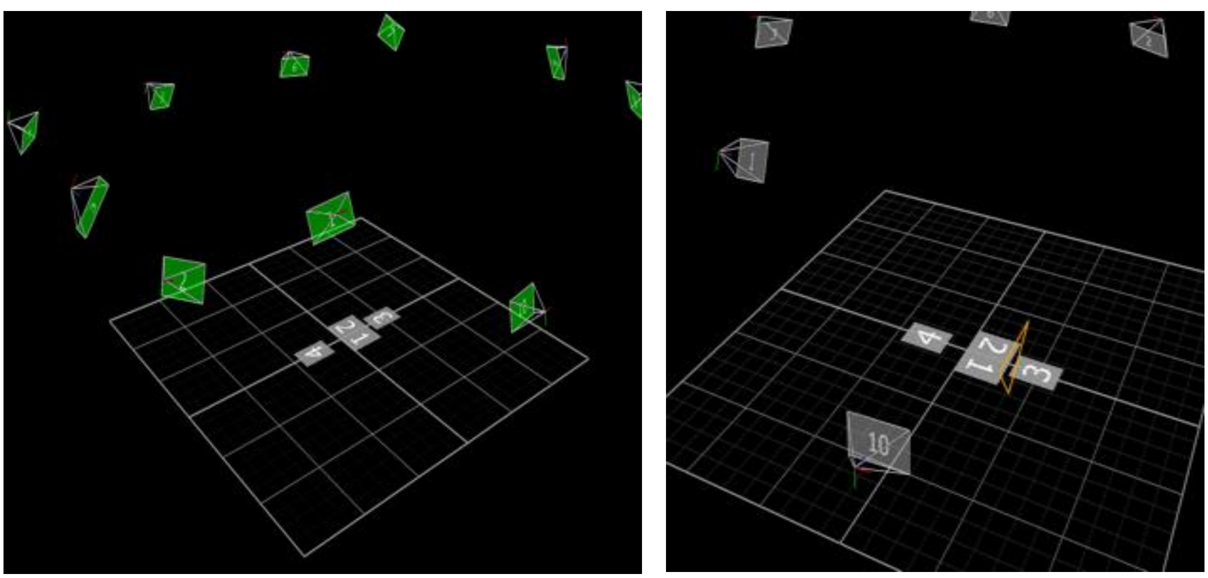

Figure 1.2. Illustration of the three-dimensional motion capture space. (*Left)* Picture of the ten-camera motion capture system, (right) 10-cm high obstacle setup. *The* length of the walkway is 8 meters long and the space for data interpretation (between the force plate # 3 and 4) is approximately 1 meter.

Electromyography (EMG)

The muscle activity the TC master's right lower extremity and right side of the trunk was recorded using a 16-channel Trigno™ Wireless EMG System (SP-W01D, Delsys Inc., Boston, MA, USA) at 2000 Hz and bandpass filtered at 20–450 Hz with a 6 db/octave-filter slope. Wireless sensors were placed on the following 10 muscles: rectus femoris (RF), adductor longus (ADDL), tibialis anterior (TA), semitendinosus (ST), erector spinae (ES), gluteus medius (GMed), tensor fasciae latae (TFL), medial gastrocnemius (MG), and lateral gastrocnemius (LG). Likewise, for the PD participants who either completed the TC or PA intervention, their muscle activity of the left and right lower extremities was recorded using a 16-channel Trigno™ Wireless EMG System (SP-W01D, Delsys Inc., Boston, MA, USA). Wireless sensors were placed on the eight muscles on left and right lower limbs: RF, ADDL, TA, ST, GMed, TFL, MG, and LG. All EMG sensor placement was performed in accordance with the SENIAM Project's guidelines (SENIAM).

Single-leg stance test with eyes open (SLO) or closed (SLC)

To perform the SLS test, the individual was asked to stand for as long as possible for up to 60 seconds, with either eyes open or closed. Trials was terminated if the individual loss their balance, or if their feet moved from the initial position. Sequence of the eyes open or closed trials were randomized. A total of three trials were collected, with three-minute rest in between. This test was selected because its strong discriminant for muscle strength in the lower extremities and its ability to reflect static postural stability (Chomiak et al., 2015; Springer, Marin, Cyhan, Roberts, & Gill, 2007).

Timed Up and Go Test (TUG)

To perform the TUG test, the individual was instructed to stand up from a chair, walk 3 meters as quick and safely as possible, cross a line marked on floor, turn around, walk back, and sit down (Lysack, 2010). The individual was permitted to use the chair's arm or back support for assistance when standing up, if needed (Morris, Morris, & Iansek, 2001). The time that he or she took to complete this task was recorded starting from the time of the instruction "go". This is a simple test of functional mobility used in the clinical setting.

Montreal Cognitive Assessment (MoCA)

For the MoCA, individual performed a series of cognitive and motor tasks by following a set of instructions. Seven cognitive domains were assessed: attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. Total time to administer the MoCA was approximately 10 minutes. The total possible score was 30 points; a score of 26 is considered normal (Nasreddine et al., 2005).

Unified Parkinson's Disease Rating Scale- motor examination (UPDRS-III)

The UPDRS-III examination was used to evaluate the severity and progression of the motor-related symptoms of PD. This scale has 14-items, each scored on a 5-point Likert scale ranging from 0 to 4, with 0 representing "no impairment" and 4 representing "marked impairment" (Fahn & Elton, 1987).

3.4 Participant preparation

Plug-in-gait Marker set

Thirty-nine reflective markers (Figure 1.3 *below*) were attached to the skin or over the participant's clothing using adhesive tape in accordance with the Plug-in-Gait marker set (Oxford Matrices), as modified from the Helen Hayes marker set (Davis, Õunpuu, Tyburski, & Gage, 1991).

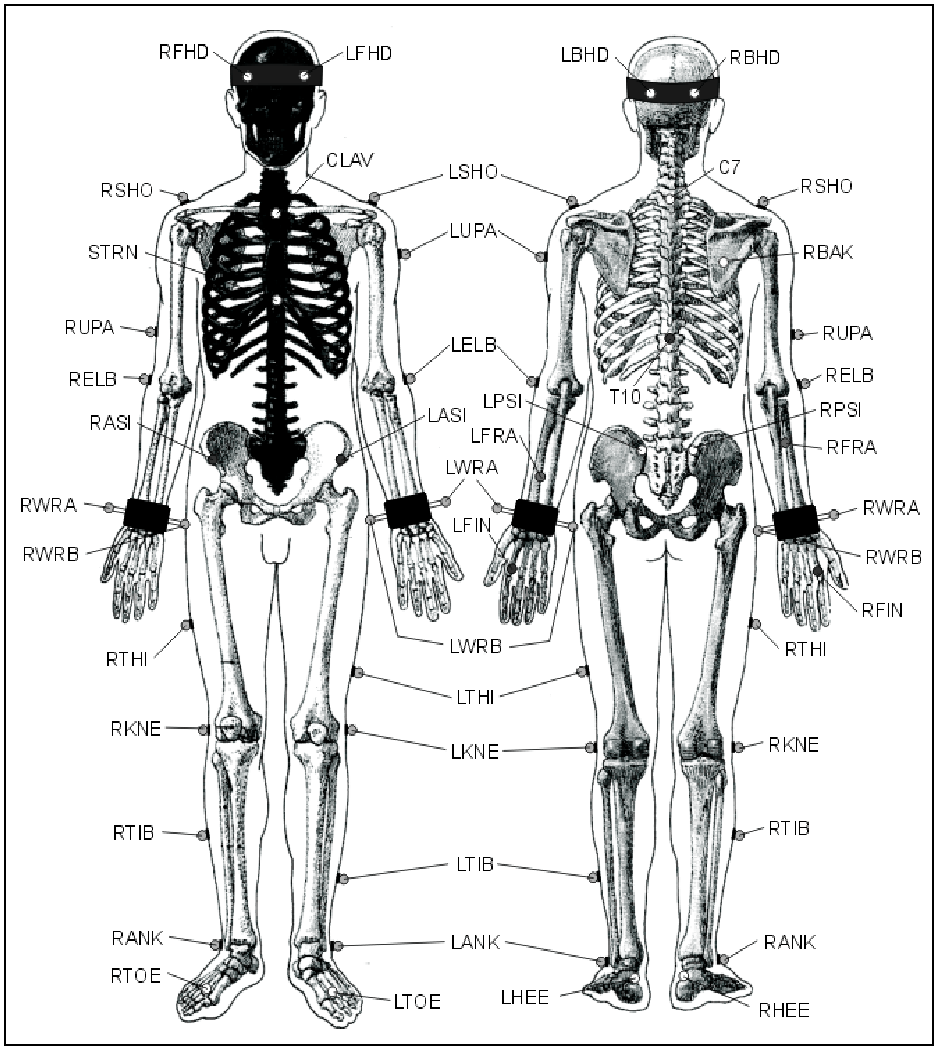

Figure 1.3. Plug-in-gait Marker set, modified from the Helen Hayes marker set. A total of thirty-nine reflective markers is placed on the participants' skin or bony landmarks.

3.5 Testing procedures

20-centimeters obstacle crossing test

The participants were required to perform five trials of obstacle crossing at their self-selected comfortable walking speed. The obstacle height was 20-centimeters high. The participants were instructed to cross with which ever limb (left or right) they preferred; the crossing limbs were classified either the leading limb (LL) or trailing limb (TL) post-collection. Two reflective markers were placed on the top left and right corners of the wooden obstacle (as shown in Figure 1.4 *below*), one marker was place on the bottom right of base holder. The obstacle was placed in the middle of the 8-meter-long walkway where the obstacle crossing trials were collected.

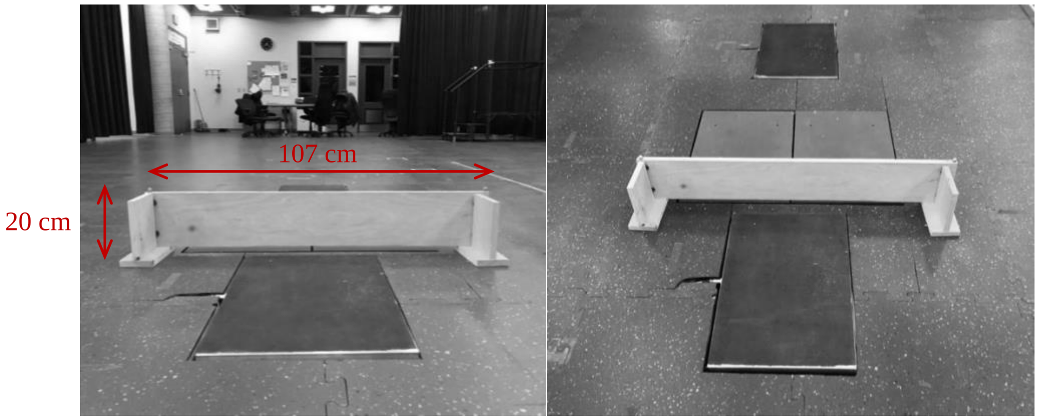

Figure. 1.4. Illustration of the 20-centimeter-high obstacle with front (*left*) and overhead views (*right*).

3.6 Online Tai Chi intervention program

Consideration in selection of Tai Chi movements

The seven TC movements were selected based on the following criteria (as outlined later in *Article 2*): 1) Easy to learn; 2) Feasible to practice; 3) Can be practiced either individually or in groups; 4) Space requirement is minimal (e.g., practicing inside the home, living room, or yard). These criteria were considered in the selection of the movements out of a possible 13 basic or classical TC movements that were derived from the Chen style (Man-Ch'ing & Smith, 2011). The selected five dynamic TC movements embodied natural movement of the body in the forward, backward, and sideway directions that are important to train postural stability and gait.

In our previous work, a biomechanics analysis was performed on two typical TC forms, the "Repulse Monkey" and "Wave-hand in cloud" (Law & Li, 2014; Li & Law, 2018). These movements had forward and backward direction movements and larger range of motion in the knee than walking. Moreover, the moment generation time for hip knee and ankle during performance were longer, indicating slow and continuous joint muscle contraction and joint loading. The "semi-deep" squatting, greater joints angles ROM, and coordinated movement patterns are unique features of TC (Chau & Mao, 2006; Wu, 2008; Wu & Millon, 2008; D. Xu et al., 2003); these elements are necessary to build muscle strength and improve joint proprioception. The consideration for the selection of the TC movements is summarized in the Table 1.1 *below*.

Table 1.1. The characteristics of the seven TC movements.

TC movement	Characteristics	Training Focus
Form #1 Wave-Hand-like-Cloud	*Dynamic* Sideway stepping: left and right	- Posture, balance - Lateral gait initiation, medial-lateral direction (ML) postural stability - Muscle strength - Eyes, arm, and trunk movement
Form #2 Brush Knee and Twist Step	*Dynamic* Forward (fwd) diagonal stepping: left and right	- Posture, balance - Fwd gait initiation, anterior-posterior direction (AP) postural stability - Muscle strength - Eyes, arm, and trunk movement
Form #3 Repulse Monkey	*Dynamic* Backward (bwd) diagonal stepping: left and right	- Posture, balance - Bwd gait initiation - Muscle strength - Eyes, arm, and trunk movement
Form #4 Leaning Fly Side	*Dynamic* Lateral diagonal stepping: left and right	- Posture, balance - ML and AP direction postural stability - Muscle strength - Eyes, arm, and trunk movement
Form #5 Starting Form	*Static* Quiet standing (arms) & vertical stretching: arms from down to up	- Posture, balance - Eyes, arm, and trunk movement coordination
Form #6 Hero Lift the Sky	*Static* Standing (arms): push up to down	- Posture, balance - Eyes, arm, and trunk movement coordination
Form #7 Standing, push back arm/hand	*Static* Standing (arms): neutral to back	- Posture, balance - AP direction postural stability - Eyes, arm, and trunk movement

The biomechanical characteristic of the seven TC movements were analyzed in study 1 and the findings obtained formed the foundation to structure the TC intervention program. The TC routine consisted of seven TC movements, three static forms and five dynamic forms. The static forms are “Push Hand Back”, “Starting Form”, and “Push Hand to Sky”. The dynamic forms are “Wave-hand in cloud”, “Repulse Monkey”, “Lateral Forward Step”, and “Brush Knee and Twist Step”. Each form had a unique movement sequence for the arms and legs, position and placement of the hands and feet. The three static forms worked to strengthen the practitioner’s stance while standing by loading and unloading their knee joints and bending or straightening the leg.

Static TC movements:

Different breathing techniques can be incorporated when performing the two static forms when to “breathe in or out”, or “how long to exhale or inhale”.

a) **“Starting Form”**, the practitioner begins by inhaling (breathing in) and raising their arm and hands up to shoulder height, exhaling (breathing out) and lowering their arm/shoulder down their side.

b) **“Push Hand Back”**, requires the practitioner to extend their arms backward and push the palms of their hands back past their body.

c) **“Push Hand to Sky”**, requires the practitioners to raise their palms up past their head toward the sky and lowering their arm/hand back to the side.

Dynamic TC movements:

During performance, the practitioner is encouraged to move their body in different directions to train balance and coordinated action of their arms and legs.

d) **“Wave-hand in cloud”**, this form is best described as a sidestepping movement that involves the practitioners moving their arm and hands in a circular action, to simulate the movement of clouds across the sky.

e) **“Repulse Monkey”**, involves the practitioners stepping **backwards**, drawing their arms/hands backward that is followed by a forward push of their palm; the left and right limbs move in a circular pattern and opposing directions.

f) **“Brush Knee and Twist Step”**, this form is the opposite of the “Repulse Monkey”, the practitioner is required to move in the **forward** direction. To perform this form, as the practitioner carefully steps forward, they focus their attention on pushing forward their palm in a circular manner; the trailing leg step should move forward with the forward pushing palm (similar side). In between each step forward, the palm that is adjacent with leading limb should “brush the knee” before the practitioner steps forward with the trailing. This action is important to train the coordination of the upper and lower limbs.

g) **“Lateral Forward Step”**, this form is like the “Brush Knee and Twist Step” in that the practitioner moves in the forward direction, but each forward step is lateral (left or right) in a 45-degree angle. As the practitioners move in the left or right directions, the palms of the hands cross across the middle of the body in the upward or downward directions to the side.

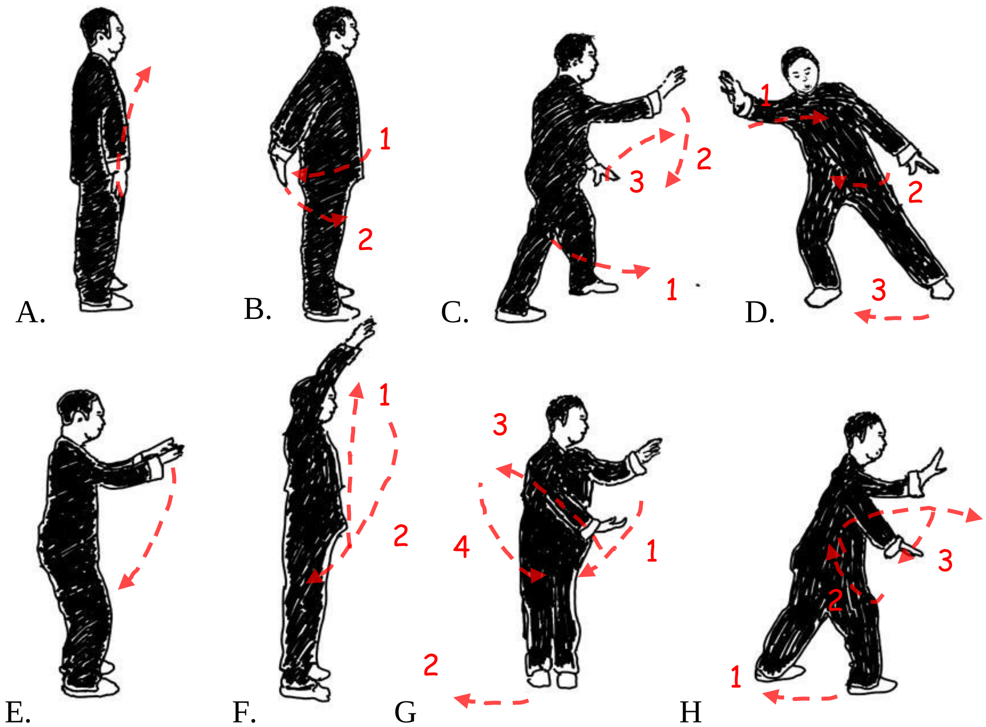

Figure 1.5. The seven selected TC movements. Their names are: Starting Form (*Letter A*), Push hand back (*Letter B*), Brush knee & twist step (*Letter C*), Lateral forward step (*Letter D*), Closing form (*Letter E*), Push hand to sky (*Letter F*), Wave-hand in cloud (*Letter G*), and Repulse Monkey (*Letter H*) are shown in the illustration. The red arrows and numbers illustrate the movement sequence of the arms and legs (*Illustration by Nok-Hin Law*).

Details of the online TC intervention program

The participants were enrolled into an online intervention that taught the TC program. The participants met online via ZOOM. Three sessions were offered weekly for 12 weeks; the participants were asked to attend at least two sessions weekly. Each session was 60 minutes and supervised by a TC instructor. The training was gradual and range from low to moderate intensity. The participants warmed up for 5–10 min, perform core activities for 40 min, and cooldown for 5 min. The seven basic TC forms (see Figure 1.5. above) were introduced with a focus on becoming comfortable with the flow and rhythm of the movements. The first two weeks of the program required the participants to work on some light breathing and simple upper limb forms. The third to sixth week of the program focused on incorporating the upper- and lower limb into the routine. These classes focused on practicing the seven TC forms sequentially. The six remaining weeks of the program focused on repetitions and performance proficiency in the basic seven-form routine. The participants were allowed to practice TC at home. Any TC that the participant performs in their home or on their own time was recorded by themselves by using a monitoring form that was distributed to them and collected weekly. The TC instructor was present at each of the session to monitor the participants' progress and to ensure that the movements are being performed correctly.

CHAPTER 4. RESEARCH ARTICLES

List of research article

Article 1: Biomechanics analysis of seven Tai Chi movements.

Published in: *Sport Medicine and Health Science* (2022) Volume 4, Issue 4, Pages 245-252

Article 2: Effects of a biomechanical-based Tai Chi program on gait and posture in people with Parkinson's disease: study protocol for a randomized controlled trial.

Published in: Trials **24**, Article number: 241 (2023)

Article 3: Gait and dynamic postural stability during obstacle crossing in the individuals with early-stage Parkinson's disease.

Submitted to: *Journal of Applied Biomechanics* (under review)

Article 4: Effects of an online 12-week Tai Chi intervention on gait and postural stability in individuals with Parkinson's disease.

In Press, Corrected Proof: Sport Medicine and Health Science, available online 11 July 2023

Article 5: Effects of an online 12-week Tai Chi intervention on the electromyography activity of the lower limb muscles of individuals with Parkinson's disease during obstacle crossing.

Ready for submission.

Research article 1

Biomechanics analysis of seven Tai Chi movements

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This article has been published in *Sport Medicine and Health Science* | Volume 4, Issue 4,

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Abbreviations:

3D: Three-dimensional

AL: Adductor Longus

ANOVA: Analysis of Variance

AP: Anterior-Posterior

BKTS: Brush Knee and Twist Step

BOS: Base of Support

COM: Center of Mass

EMG: Electromyography

ES: Erector Spinae

GM: Gluteus Medius

iEMG: Integrated Electromyography

LFS: Lateral Forward Step

LG: Lateral Gastrocnemius

MG: Medial Gastrocnemius

ML: Medial-Lateral

RF: Rectus Femoris

RM: Repulse Monkey

ROM: Range of Motion

SENIAM: Surface Electromyography for the Non-Invasive Assessment of Muscles

ST: Semitendinosus

TA: Tibialis Anterior

TC: Tai Chi

TFL: Tensor Fasciae Latae

WHIC: Wave-hand in Cloud

Abstract

This study examined the maximum joint angles and moments, and electromyography (EMG) activity of the lower limbs in an experienced Tai Chi (TC) practitioner in performing four dynamic (Repulse Monkey, Wave-hand in Clouds, Brush Knee and Twist Step, and Lateral Forward Step) and three static TC movements (Starting Form, Hero Touch Sky, and Push Hand Back) and compared them with the measures from walking. Integrated EMG (iEMG) and peak EMG of the rectus femoris, adductor longus, tibialis anterior, semitendinosus, erector spinae, gluteus medius, tensor fasciae latae, medial and lateral gastrocnemius muscles were analyzed. One-way analysis of variance showed that compared with walking, TC presented 1) significantly larger hip flexion (71.4° vs. 42.2°) and abduction angles (11.9° vs. 5.3°), smaller knee flexion (45.2° vs. 71.1°) and abduction angles (13.0° vs. 27.7°), larger ankle dorsiflexion (41.4° vs. 11.3°) and abduction angles (8.8° vs. 7.2°); 2) hip flexion moment and knee flexion and abduction moment were significantly larger. Ankle dorsiflexion moment were significantly smaller, whereas ankle abduction moment was significantly larger in two TC movements; and 3) the EMG activity of the muscles in TC varied from 10% to 610% of walking. The knee extensors, hip adductors and abductors had significantly higher peak EMG (430% ± 40%, 240% ± 30%, and 320% ± 90%) and iEMG values (610% ± 30%, 311% ± 30%, and 1.4% ± 20%), respectively. The findings suggested that these TC movements could be a good option for the improvement of muscle strength and range of motion of the lower limbs.

Keywords: joint angles, joint moments, EMG, Tai Chi, walking.

Introduction

Tai Chi (TC) is a traditional Chinese exercise practiced in China and around the world owing to its beneficial effects on health. Regular TC practice is well documented to enhance physical and mental health.[1,2] Particularly, TC training leads to improved muscle strength, balance, and posture that contribute to reducing the risk of falls in the elderly.[3,4] The *American* and *British Geriatric Societies* recommends practicing TC to prevent falls in older adults.[5] Given that TC can be practiced at home or outdoors, require no facility, and has gentle motion features, TC training has big potential for health promotion and the management of some chronic conditions associated with poor posture control and falls, such as Parkinson's disease.

One of the most remarkable findings in TC training is its beneficial effects on postural stability in the medial-lateral (ML) direction.[6] The terms "balance" and "postural stability" are often used interchangeably. Balance refers to a state in which the body is in equilibrium,[7] whereas postural stability is defined as the ability to control of the body's position in space for the purposes of balance and orientation.[8] Research has shown that the decline in postural stability in the ML direction is closely associated with falls and the re-occurrence of falls in elderly people.[9] Moreover, TC training can improve awareness of the body's movements and joints' proprioception and can provide appropriate joint loading of the lower limb.[10] Thus, TC training could strengthen and enhance the neuromuscular reaction of muscles in the lower extremities related to postural control and balance.[11,12] To improve postural stability in the ML direction could help to reduce falls in the elderly. However, why regular TC training can improve postural stability in the ML direction is unknown. To enhance our understanding of this question, a biomechanical analysis of TC movement is needed.

Several kinematic and kinetic studies of TC movements have been published. These studies have examined the biomechanical characteristics of a few TC movements such as Push Hand, Brush Knee and Twist Step (BKTS), as well as TC stepping.[13–15] Kinematic analysis of TC movements demonstrates that compared with walking, TC movements present a significantly larger three-dimensional (3D) movement in the forward, backward, and sideway directions, a significantly larger range of motion (ROM) of the joint of the lower limbs,[15–17] and double-limb support times.[14,15] A kinetic study of TC stepping has shown that compared with walking, TC stepping has significantly smaller peak compressive forces, larger peak shear forces in the ankle, knee and hip joints, and larger peak moments in the knee and hip joints.[18] Larger hip abduction and extension moments have been reported during the performance of two TC movements, the Repulse Monkey (RM) and Wave-hand in Clouds (WHIC) compared with the hip joint abduction and extension moments of walking.[19] The results of the study reveal that TC differs from the joint-moment patterns of walking, the peak moment generation time is much longer during TC performance, and the joint moments are active across an entire gait cycle. Thus, TC could be a safe and effective training for the elderly.

Muscle activity during TC performance has also been explored. The earliest study, published in 2003, examined the muscle activity of the trunk and lower limb during push-hand movement and BKTS using electromyography (EMG).[13,20] Push-hand movement generates high muscle activity in the lumbar erector spinae and the rectus femoris. Concentric and eccentric contractions occur in muscles of the lower limbs.[13] During the performance of BKTS and TC stepping, the activation of the lower limb muscles is slow and coordinated, and the activity level is higher than that during walking.[16,20] In 2007, an EMG study revealed that the TC activation level of knee muscles is higher than that during walking.[21] Nevertheless, muscle activity during TC is poorly understood despite the growing interest and popularity of TC.[22] Moreover, an integrative and synchronized study on kinematics, kinetics, and muscle activity during TC is lacking, which limits the understanding of the biomechanics of TC movements.

To practice TC for health promotion and chronic diseases management for the elderly, particularly to improve postural stability and fall prevention, attention must be paid to two aspects. First is its *feasibility*. Many traditional TC styles exist, and they vary in the number of TC movements, ranging from 24, 48, and up to 108 forms. Learning and practicing these TC movements would be exceedingly difficult for the elderly. Second is e*ffectiveness*. To structure a short, feasible, and practical TC program for the elderly, the selection of TC forms is critical because the movement characteristics are some of the factors influencing the training effects. Thus, selecting the TC movements should be based on the biomechanical study of TC movement that would help in developing a feasible, practical, and effective TC program.

The present study aimed to examine the kinematics, kinetics, and muscle activity of the lower limb in performing seven selected TC movements. Biomechanical measures from TC were compared with the measures from walking, a popular physical activity for the elderly. The selected TC movements are common forms of the traditional TC styles such as Wu, Yang, and Taoist styles of TC and are believed to represent the classical movements of TC.[23,24] These TC movements are Starting Form, Hero Touch Sky, and Push Hand Back, BKTS, RM, WHIC, and Lateral Forward Step (LFS). We hypothesized that significant differences existed in joint angles, joint moments, and muscle activity of the lower limbs between TC and walking. The information obtained from this study could enable further understanding of the mechanism of the beneficial effects of TC on improving postural stability and could provide scientific recommendation in developing a TC training program for the elderly.

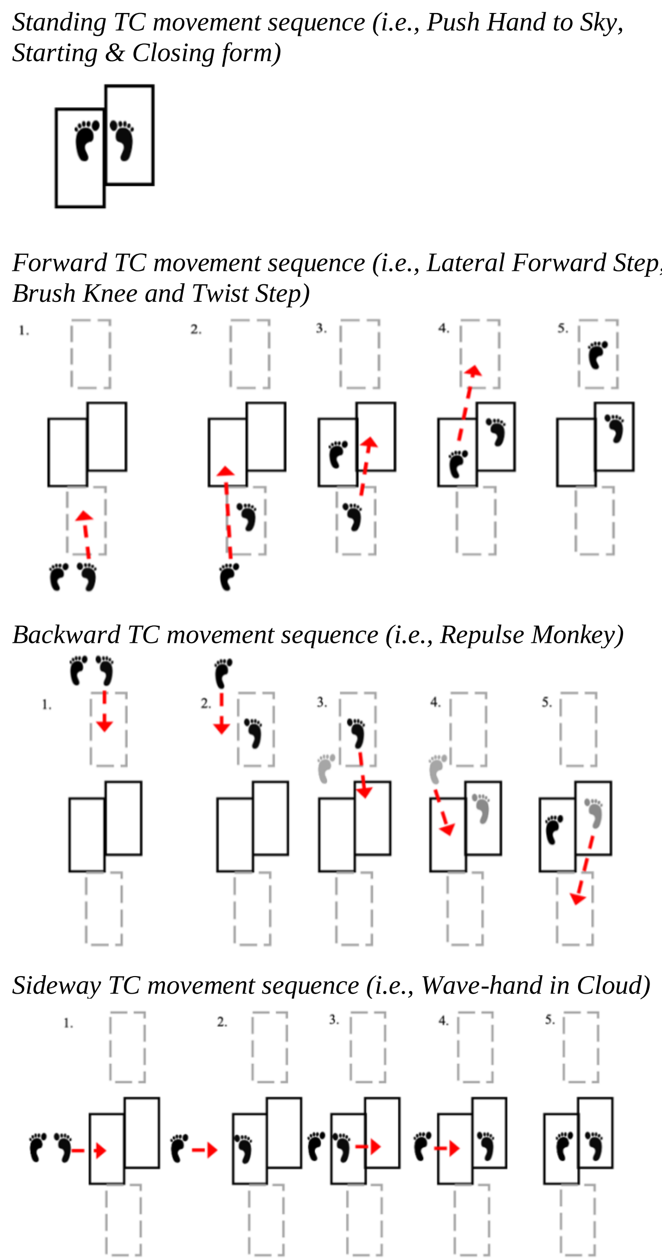
Methods

Participants and Tai Chi Movements Selection

One TC master (*n* = 1; age, 38 years old; body weight, 84.2 kg; height, 176.5 cm) with more than four years of Wu style TC experience was recruited for this study. This study was approved by the University of Ottawa Health Science and Science Research Ethics Board. Informed consent from the participant was obtained. Selection of TC movements were based on our previous TC biomechanical research[15,19] and TC literature.[23,24] These TC movements are typical TC movements included in the Wu, Yang, and Chen TC styles.[23,25] The selection considerations were as follows: 1) easy to learn, 2) feasible to practice, 3) involves large motion in different direction, such as anterior-posterior (AP) and ML directions, and 4) includes static and dynamic motion. A *static* TC movement was defined as the movement in which the center of mass (COM) was maintained within the limits of the body's base of support (BOS), whereas a *dynamic* TC movement was defined as the movement in which the body's COM was outside the limits of the body's BOS.

Data Collection

Thirty-nine reflective markers were attached to the skin or over the participant's clothing using adhesive tape in accordance with the Plug-in-Gait marker set (Oxford Matrices), as modified from the Helen Hayes marker set.[26] A Vicon motion-analysis system comprising 10 infrared tracking cameras (two Vicon Vantage cameras (model v5) and eight Vicon Vero cameras (model v1.3); Oxford Metrics, Oxford, UK)) was used to capture the TC movements and walking trials at 200 Hz. Ground reaction forces were recorded using four force plates at 2000 Hz (models 9286AA, Kistler Instruments Corporation, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA) embedded in the middle of an 8 m-long walkway. The two Kistler force plates were positioned in the middle of the walkway and configured in a staggered position, with the two Bertec AMTI force plates positioned at the ends (Figure 2.1 *below*). The setup of the force plates allowed the TC master to perform each TC movement comfortably at different starting points and allowed them to move forward, backward, or sideways across the force plates.



Figures 2.1. Configuration of force plates for TC movement performance. The (red) indicate the direction of each step. The two black outlined rectangles are to illustrate the two Kistler force plates, while the two dotted-line outlined rectangles are the two Bertec AMTI force plates. The gray foot illustrate "toe-touch", in which the body weight disturbtion is 40% in the front leg, 60% in the back leg.

The muscle activity of the right lower extremity and right side of the trunk was recorded using a 16-channel Trigno^{TM} Wireless EMG System (SP-W01D, Delsys Inc., Boston, MA, USA) at 2000 Hz and bandpass filtered at 20–450 Hz with a 6 db/octave-filter slope. Wireless sensors were placed on the following 10 muscles: rectus femoris (RF), adductor longus (AL), tibialis anterior (TA), semitendinosus (ST), erector spinae (ES), gluteus medius (GM), tensor fasciae latae (TFL), medial gastrocnemius (MG), and lateral gastrocnemius (LG). EMG placement was performed in accordance with the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) Project's guidelines.[27] The participant was asked to perform seven TC movements, including three static (Starting Form, Hero Touch Sky, and Push Hand Back) and four dynamic (BKTS, RM, WHIC, and LFS) movements, as well as walking for 10 trials at a comfortable pace.

Data Processing and Analysis

The 3D joint angles and moments for the lower limbs were obtained using Vicon Nexus (Oxford Metrics) and the Plug-in-Gait model (Oxford Metrics). A total of five collected trials for each TC movement were selected for analysis based on the consistency of the visually inspected TC stepping pattern along the sagittal and frontal planes. One gait cycle was identified from each trial for data analysis. A gait cycle was defined from the instance of foot contact to the subsequent foot contact of the same foot for walking and the four dynamic TC movements. Foot-strike and foot-off were determined by a combination of visual inspection of the position of the virtual heel and toe markers and the detection of the contact and take-off points by the force plates. For the kinematic and kinetics parameters, the computed joint angles and joint moments of the hip, knee, and ankle along the frontal and sagittal planes were exported to MATLAB (MathWorks, Natick, USA) to average and calculate the maximum and minimal values of each trial of the movement. Joint angle and moment data were normalized to one gait cycle.

EMG data were processed using a custom MATLAB (MathWorks, Natick, USA) script. The EMG signals of the lower limb muscles was filtered with a third-order Butterworth bandpass filter at 20–500 Hz, full-wave rectified, down sampled to 200 Hz, and filtered with a second-order low-pass filter at 6 Hz to remove any noise in the signal. For the TC movements and walking trials, a 5-second sample of the EMG signal was collected from the start of the first right-heel-strike event. The peak EMG amplitude (peak EMG) value and integrated EMG (iEMG) value were calculated within a 5-second window for each trial of TC movements and walking trials. The maximum EMG and iEMG values of the TC movements were normalized by the averaged value of the walking trials and reported as a ratio of the value obtained from walking.

Descriptive statistics were reported for the measures using SPSS version 20 for Windows (SPSS Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) (TC movements: seven levels vs. walking) was used to compare the joint angles, joint moments, iEMG, and peak EMG values. To control for type I errors when performing multiple independent t-tests, Bonferroni correction was used for post-hoc analysis. The significance level was set at 0.05.

Results

Table 2.1 shows the mean and standard deviation of the maximum joint angles and moments during the performance of the four dynamic TC movements and walking. The hip flexion and abduction angles were significantly greater for the TC movements except for WHIC and LFS, respectively, ($p \leq 0.001$ vs. walking). Knee flexion and abduction angles were smaller for all TC movements, notably for BKTS and WHIC ($p \leq 0.05$ vs. walking). Dorsiflexion angles for the TC movements were significantly larger than walking. Compared with walking, hip flexion moments were significantly larger for LFS and RM ($p \leq 0.001$ vs. walking). Knee flexion and abduction moments were significantly larger for the TC movements, except the abduction moment during WHIC. Dorsiflexion moments were significantly smaller during LFS and RM movements, whereas abduction moments were significantly larger during LFS and WHIC.

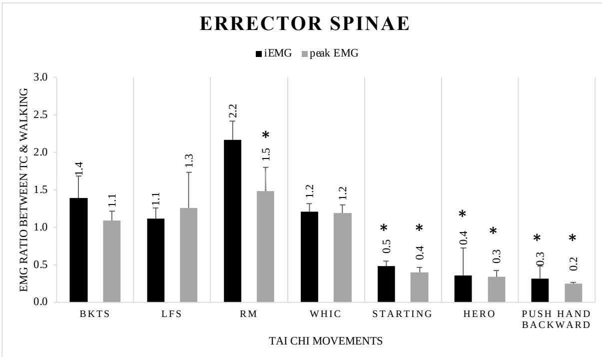
Figure 2.2 illustrates the ratio of iEMG and maximum EMG of the 10 selected muscles of each TC movement compared with walking. The EMG activity of the lower limb muscles in TC varied from 10% to 610% of walking. The adductor longus iEMG and maximum EMG values were significantly larger for all TC movements, except for the maximum EMG value of BKTS. The maximum values of the gluteus medius were significantly larger for three of the four dynamic TC movements, whereas the maximum values of the tensor fasciae latae were significantly larger for BKTS and LFS. The iEMG values from biceps femoris were significantly larger during the dynamic TC movements, except for WHIC. The iEMG and maximum EMG values of the semitendinosus were significantly larger during BKTS ($p \leq 0.001$). The semitendinosus iEMG values were significantly larger for all TC movements, except RM and Hero. Compared with walking, significantly larger iEMG and maximum EMG values of rectus femoris were observed in the four dynamic TC movements, except the maximum EMG values for WHIC. Significantly larger iEMG and maximum values of the medial gastrocnemius were found for all TC movements, except for the maximum EMG value of WHIC.

Table 2.1. Mean and standard deviation (brackets) of the maximum hip, knee, and ankle angle and moment for the four dynamic Tai Chi movements and walking during a gait cycle (*n* = 1).

Measures	Walking	BKTS	LFS	RM	WHIC
Angles (°)					
Hip Flexion	42.0 (2.4)	71.4 (1.6)*	61.2 (2.1)*	67.2 (1.1)*	40.7 (1.6)
Hip Abduction	5.3 (1.2)	11.9 (0.9)*	5.6 (1.1)	9.4 (0.8)*	9.2 (0.5)*
Knee Flexion	71.1 (1.9)	69.0 (1.2)**	65.1 (3.1)	45.2 (2.3)	68.3 (2.7)*
Knee Abduction	27.7 (2.4)	13.0 (2.4)*	25.1 (1.5)	26.9 (0.8)	22.4 (2.7)**
Ankle Dorsiflexion	11.3 (0.9)	37.7 (1.7)*	40.9 (1.0)*	41.4 (1.1)*	29.5 (1.8)*
Ankle Abduction	7.2 (1.0)	3.4 (0.2)*	8.6 (0.5)**	8.8 (0.4)**	6.1 (0.4)**
Moments (N·m/kg)					
Hip Flexion	1.0 (0.2)	1.1 (0.0)	1.5 (0.1)*	1.2 (0.1)*	0.9 (0.1)
Hip Abduction	0.7 (0.4)	0.8 (0.1)	0.5 (0.1)	0.7 (0.1)	0.4 (0.1)
Knee Flexion	0.5 (0.2)	1.3 (0.1) *	0.9 (0.1)*	1.0 (0.0) *	0.8 (0.1) *
Knee Abduction	0.6 (0.2)	0.9 (0.1)**	0.9 (0.0)**	1.0 (0.1)*	0.6 (0.1)
Ankle Dorsiflexion	1.2 (0.1)	1.1 (0.1)	1.2 (0.1)	0.9 (0.0)**	0.8 (0.1)*
Ankle Abduction	0.1 (0.1)	0.1 (0.0)	0.3 (0.0)**	0.2 (0.0)	0.4 (0.1)*

BKTS: Brush Knee and Twist Step, LFS: Lateral Forward Step, RM: Repulse Monkey, WHIC: Wave-hand in Cloud.

* $p \leq 0.001$, vs. walking; ** $p \leq 0.05$, vs. walking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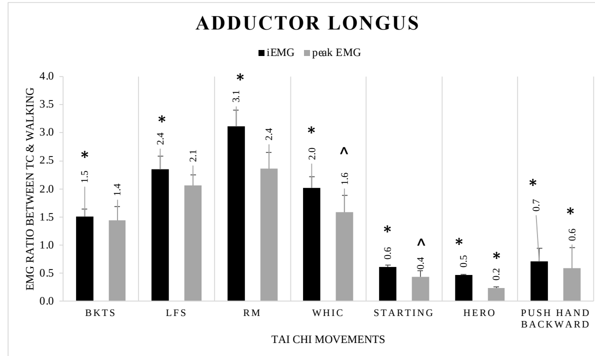
TAI CHI MOVEMENTS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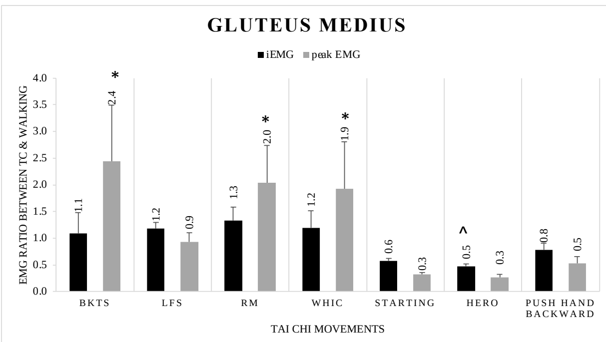
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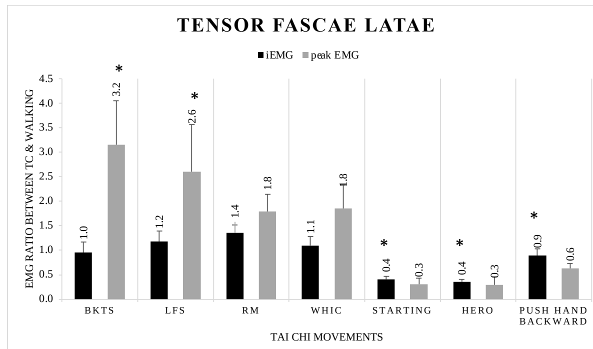
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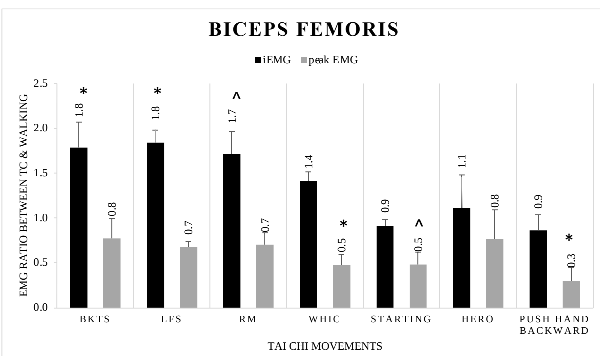
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EMG RATIO BETWEEN TC & WALKING
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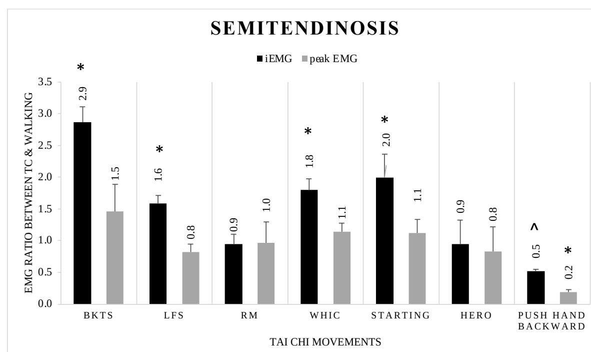
LFS
RM
WHIC
STARTING
HERO
PUSH HAND BACKWARD
TAI CHI MOVEMENTS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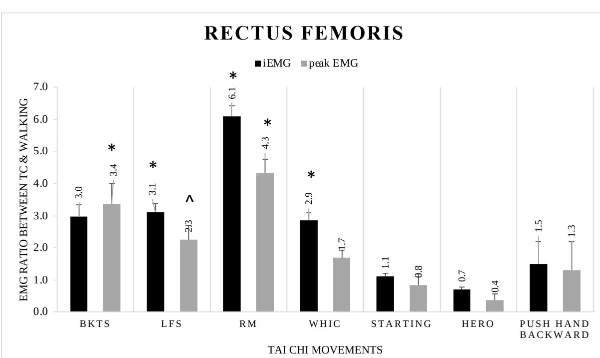
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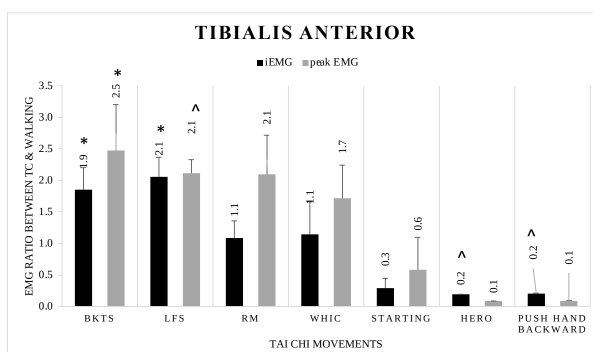
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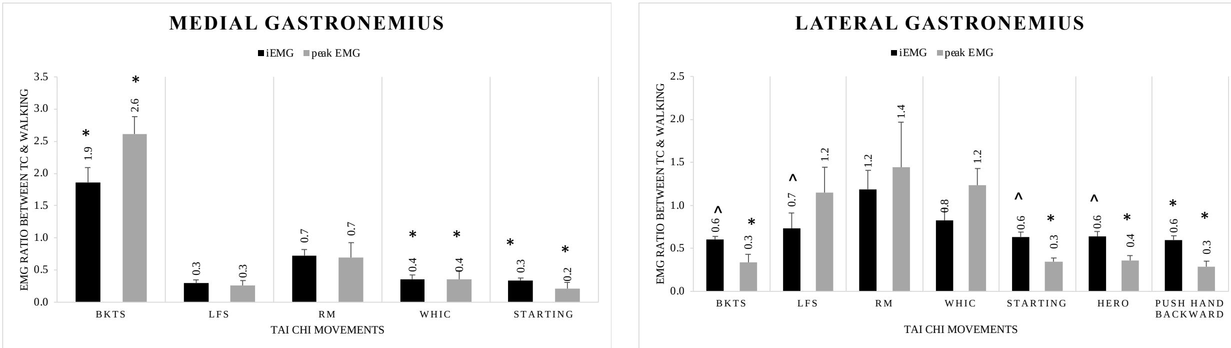

Figure 2.2. Illustration of the ratio of integrated electromyography and maximum electromyography (EMG) values of each Tai Chi movement to walking values of each muscle. BKTS: Brush Knee and Twist Step, EMG: electromyography, iEMG: integrated EMG, LFS: Lateral Forward Step, RM: Repulse Monkey, TC: Tai Chi, WHIC: Wave-hand in Cloud. The left bottom chart of medial gastrocnemius does not include the EMG data values from two static Tai Chi movements because the EMG signal were missing due to problems with the EMG sensors' batteries. * $p \leq 0.001$, vs. walking; ^ $p \leq 0.05$, vs. walking.

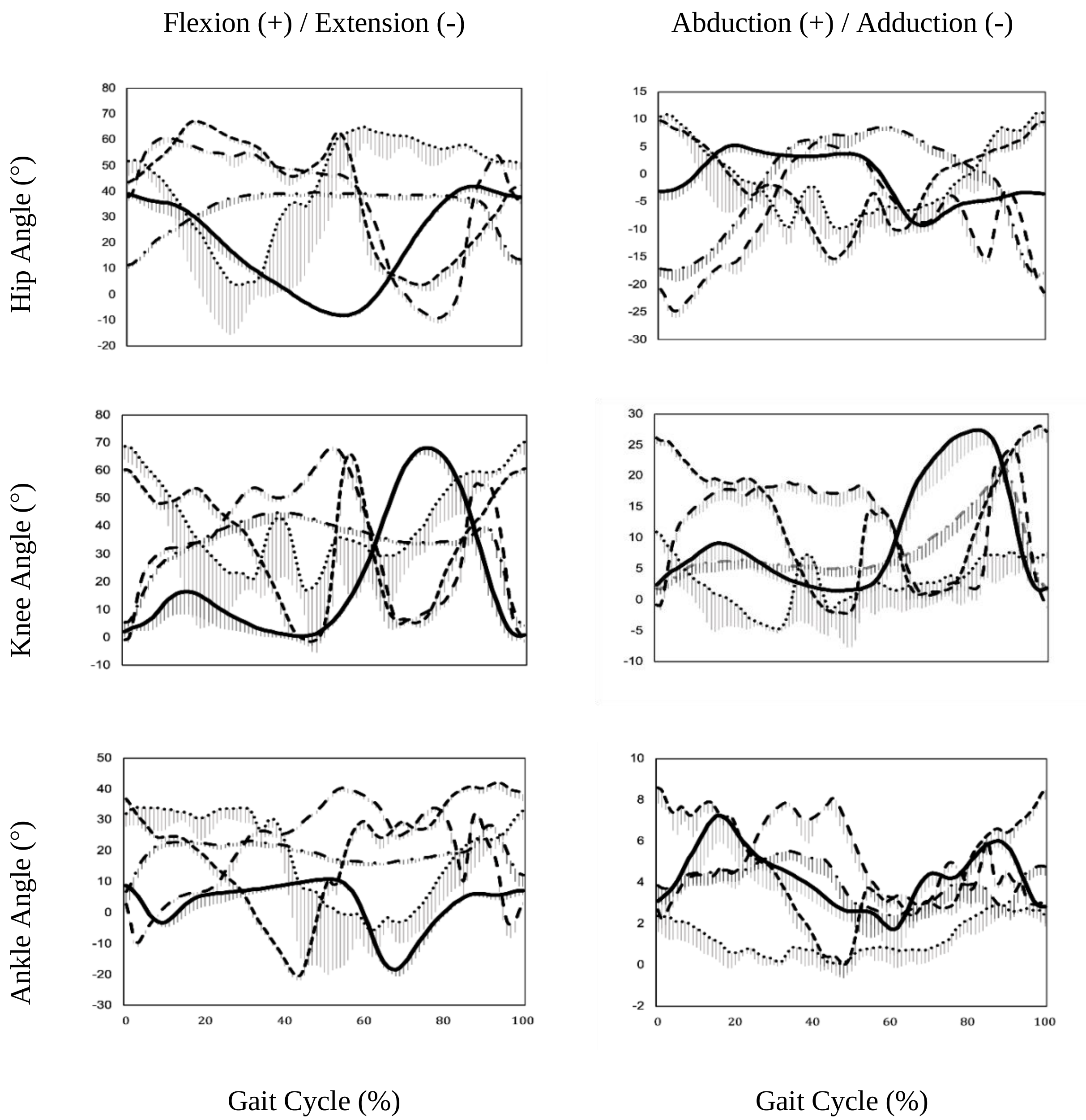

Figure 2.3. Angular displacement of the hip, knee, & ankle in sagittal (left column) and frontal plane (right column) during one gait cycle of walking (solid line) and four Tai Chi movements, lateral forward step (wide dash), repulse monkey (narrow dash line), wave-hand in cloud (dash-dot line) and brush knee & twist step (dotted line).

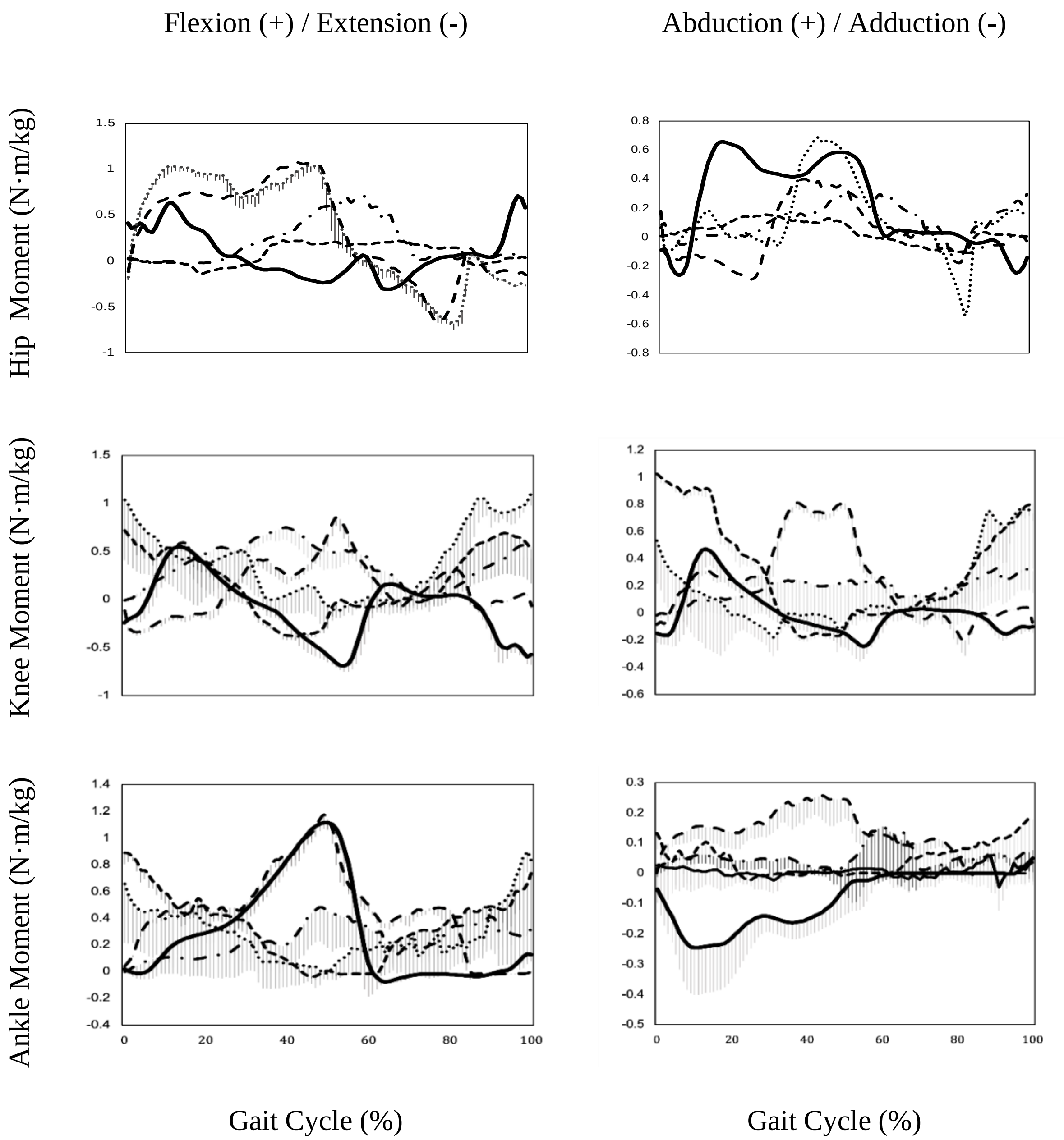

Figure 2.4. Joint moment patterns of in sagittal plane (left column) and frontal plane (right column) during one gait cycle of walking (solid line) and four Tai Chi movements, Lateral Forward Step (wide dash), Repulse Monkey (narrow dash line), Wave-hand in Cloud (dash-dot line) and Brush Knee and Twist Step (dotted line).

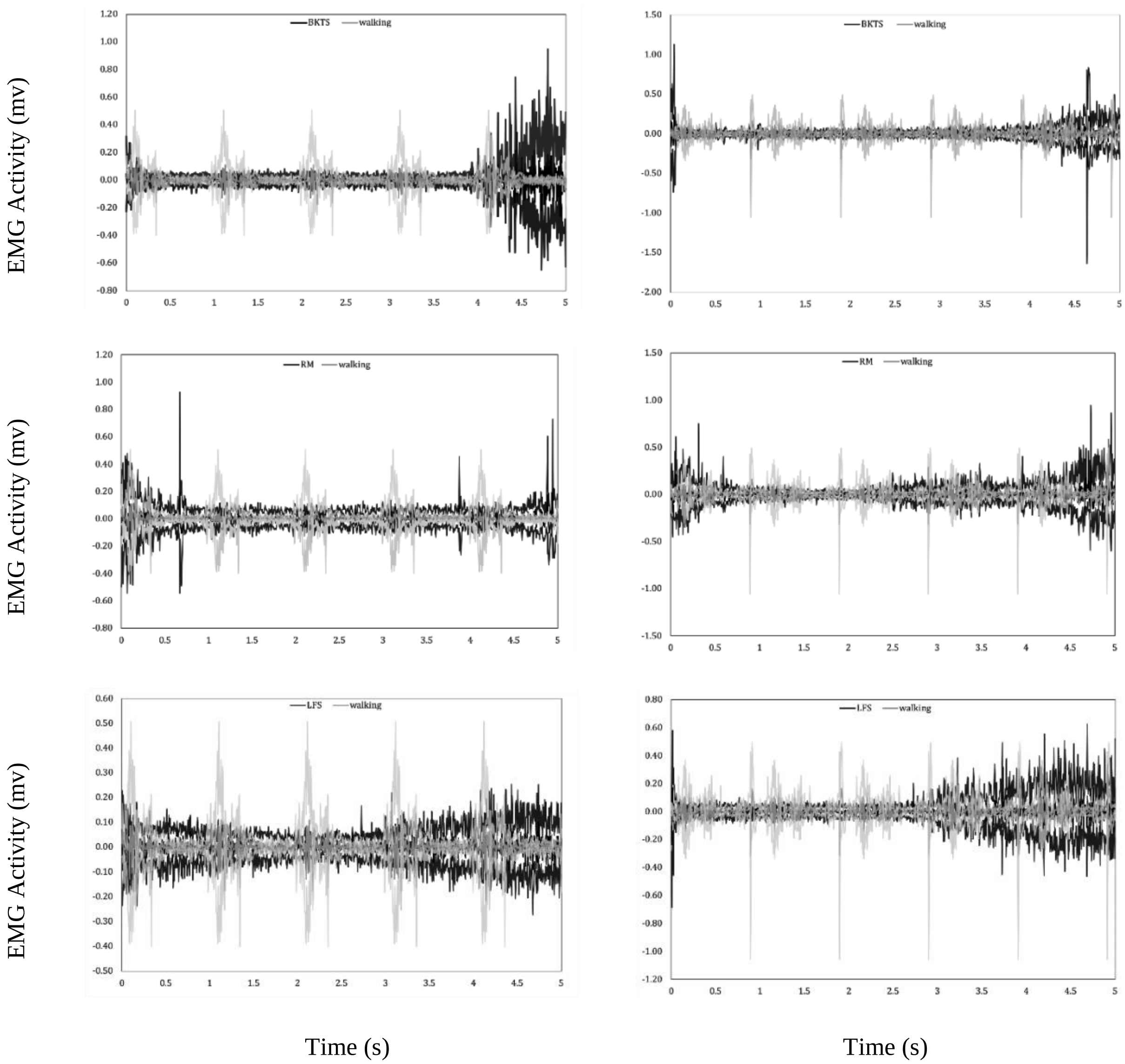

Figure 2.5. Electromyography activity of the gluteus medius (left column) and tensor fasciae latae (right column) during performing Brush Knee and Twist Step (top), Repulse Monkey (middle), and Lateral Forward Step (bottom). BKTS: Brush Knee and Twist Step, EMG: electromyography, LFS: Lateral Forward Step, RM: Repulse Monkey.

Discussion

This study examined the joint angles, joint moments, and muscle activity of seven TC movements and compared them with the measures from walking. Our main findings were as follows: compared with walking, 1) most dynamic TC movements (i.e., BKTS, WHIC, RM, LFS) presented significantly larger hip flexion and abduction angles and ankle dorsiflexion and abduction angles; 2) significant joint moment between TC and walking were found at the hip, knee, and ankle joints, particularly in hip and knee flexion moments and knee abduction moments; and 3) for both the static and dynamic TC movements, performing these TC movements resulted in stronger muscle activity of the lower limb, particularly in hip abductor and adductor muscles.

Significant differences were found between TC and walking in the joint angles of the hip, knee, and ankle. TC had significantly larger maximum hip flexion and abduction angles and ankle dorsiflexion and abduction angles than walking. Changes in joint angle (Figure 2.3) were found in the early part a gait cycle, and the hip joint remained flexed in stance phase (0%–60% gait cycle) when performing TC, whereas the hip started into extension in the early-stance phase (0%–20% gait cycle) when walking. At the knee joint, more joint angle variations and changes occurred in the early-stance phase during TC than during walking. The evidence was consistent with the findings reported from a few published TC kinematic studies.[15,28] The joint angles of the lower limb have been studied in several TC movements, including BKTS, RM, and WHIC. The earliest study examined joint kinematics during BKTS performance in six experienced TC masters and reported a wide ROM of the knee and ankle joints.[20] Later, kinematics analysis of gait cycle time, single leg and double leg stance time, and joint angles, as well as ROM of lower limb, were examined during RM and WHIC performing by older TC practitioners with more than four years of experience.[15] Their results show that WHIC has significantly larger movement angles at hip and ankle joint than walking, whereas RM shows significantly larger knee joint angles than walking.

The larger joint angles and motion of lower limb in three of four TC movements reported in the current study further supported a previous study on the ROM of the ankle and knee joints during five movements of 42-form TC (BKTS, RM, WHIC, Kick Heel to Right, and Grasping the Bird's Tail) in a young TC master.[17] A larger ROM of the ankle and knee joints was reported in TC than normal walking data.[15] The current study showed larger angles of the hip and ankle during TC but not of the knee. The difference in knee joint angles may be related to the variation in TC style between the Wu style TC studied in the current study and the 42-form TC in the aforementioned study. 42-form TC is defined as a TC form for professional competition with a high requirement of knee-joint motion. Studies have demonstrated that larger angles of hip rotation and ankle dorsiflexion ROM are positively correlated with dynamic balance in young and older adults.[29,30] Good flexibility and lower limb joints ROM are necessary for dynamic balance to be maintained. A reduction in the plantarflexion is linked with poor ankle power generation.[31–33] Indeed, poorer maximal sole inclination and reduced plantarflexion angle of the ankle has been reported in fallers and elderly populations.[34,35] Exercise training is shown to help increase plantarflexion angles and improve the ability to perform certain functional activities such as walking.[36,37] The larger hip ROM and ankle dorsiflexion ROM in this study correspond with better performance on balance tests. Research has shown that lateral instability can lead to greater falls and injuries when the body is perturbed.[38] The hip abductors/adductors help to maintain lateral stability and balance during all phases of standing and walking.[39] Imbalance in the agonist and antagonist hip muscles would cause instability to the pelvic region,[40] thereby restricting dynamic range of motion of the hip joint that can lead to possible problems and high fall risk.[41] Thus, larger

ROM or maximum angles of the lower extremity during TC could help improve muscle strength and balance control. Regular TC practice could be a good exercise option for improving the ROM of the lower limb and subsequently contributing to improved postural stability.

This study found significant differences in the flexion and abduction moments of the hip, knee, and ankle joints between TC movements and walking, respectively. Our previous study[19] has examined the joint moment of hip, knee, and ankle during RM and WHIC performance and found larger flexion/extension moments at the hip. Significantly larger flexion moments at the hip were found in two TC movements, namely, LFS and RM movements, consistent with previous findings. The current and the previous studies showed smaller dorsiflexion moments in for RM and WHIC. Wu and colleagues studied joint kinetics in young (n = 6) and old (n = 6) TC practitioners.[42] They found that abduction/adduction moments at the hip, knee, and ankle joints during TC stepping increased compared with walking.[18] Together with our study, research evidence in joint moments of the hip, knee, and ankle during TC were basically consistent. The EMG activity of the lower limb muscles from this study also indicated that stronger muscle activity that could contribute to higher joint moment.

The joint-moment patterns (Figure 2.4) suggested that the loading pattern at the joint of the lower limb during TC performance differed from that in walking. During a gait cycle, most TC movements were maintained at a higher level and longer lasting period than those in walking. Studies have shown that regular exercise and physical activity can help to deter the loss of muscle mass,[43-46] maintain and enhance the synthesis of new articular cartilage,[47] and to prevent loss of bone mineral density by repetitive loading the joint.[48] Since muscles generate forces which act across the knee and ankle joints, increasing amount and time of loading on the joints would help to train the muscles.[49] Maintain a higher and longer loading rate would strengthen and improve endurance of the muscles that help to stabilize the joint. During TC, semi-squatting posture and gentle foot touchdown keeps the hip, knee, and ankle in a flexed position,[19] generating higher flexion moments at the joints. Long-term TC practice is shown to help improve proprioception of the knee and ankle joints.[50] Our previous study has shown that the time-to-maximum moment generation takes a significantly longer time to reach for TC than for walking.[19] This finding suggested that muscles of the hip, knee, and ankle are more active during TC than walking.

The higher flexion joint moment at hip and knee during TC performance are similar to those observed during the performance of squat exercises. One study has examined joint moment during a squat to self-selected depth (normal squat) and a squat onto a chair with a standardized height of 43.8 cm in 20 older adults (aged 70–85).[51] Research has shown that the squats can increase either hip or knee joint moments, which can be recommended to health workers in prescribing exercise for older adults to improve muscle strength. In the current study, four dynamic TC movements showed increased flexion moment of the hip and knee than walking, suggesting that performing the four TC movements could require more muscle activity of the hip and knee. Thus, the four TC movements could be prescribed for older adults to improve muscle strength.

We conducted synchronized analysis on the EMG activity of the lower limb with joint angles and joint moments during TC performance for the first time. Moreover, the muscle activities of hip abductor/adductor muscles closely attributed to postural stability in the ML direction were examined for the first time. Results showed that the hip abductors (gluteus medius and tensor fasciae latae) and hip adductor (adductor longus) presented either significantly stronger iEMG or maximum EMG activities during dynamic TC movements than walking. The EMG signal patterns of gluteus medius and tensor fasciae latae (Figure 2.5) showed the higher magnitude of EMG signals and longer duration of EMG activity in TC movements than walking.

Our findings suggested that performing these TC movements enabled the activation of more muscle fibers and had stronger training effects on these muscles than walking. Gluteus medius, tensor fasciae latae, and adductor longus muscles were attributed to ML postural stability and countermovement stabilization during the event of a sideward fall. Neuromuscular control from the muscles of the hip joint helps regulate the movement of the pelvis and trunk while moving.[52,53] Research has demonstrated that older people seem to prioritize the hip strategy to maintain postural stability.[54] However, aging-related deficit in hip strategy, especially in the ML direction, has been documented.[55] The decline in postural stability in the ML direction is closely associated with falls and their re-occurrence in elderly people.[9] Muscle weakness is one of factors leading to postural-stability deficiency in elderly people.[56] Weak hip muscles affect the stability of the joint and reduce the effectiveness of hip-stabilization strategies, thereby increasing the risk of falls and injuries.[57,58] Thus, maintaining and enhancing the muscle strength of hip abductors and adductors have been addressed for fall prevention. Based on the EMG findings of dynamic TC movements, regular TC practice can help train the hip muscles, particularly those responsible for ML stability.

EMG analysis of erector spinae, rectus femoris, tibialis anterior, semitendinosus, medial gastrocnemius, and lateral gastrocnemius during the performance of dynamic TC movements showed higher muscle activity than in walking. Chan and colleagues examined the iEMG of lower limb muscles when performing push hand performance by one TC master with more than 22 years of TC practice.[13] They found that iEMG in the medial hamstring and gastrocnemius muscles during push hand were about 20% to 68.3% of the iEMG of maximum voluntary muscle contraction. Push-hand performance requires a double leg-standing posture. In the present study, the static TC movements were in double leg-standing posture. The EMG activity of the lower limb during static TC movements ranged from 0.2 to 2.0 times of EMG in walking (~20% to 200% of walking's

EMG). The difference in EMG data normalization between the abovementioned study and the current one makes comparison of the findings difficult. Wu and colleagues studied the EMG activity of lower limb during TC gait/stepping in young TC practitioners with four months of experience compared with the EMG activity during walking.[16,38] They found a higher magnitude (200%–400%) of the tibialis anterior, rectus femoris, and tensor fascia latae muscle activities and a longer duration of co-activation of most leg muscle pairs (130%–380%). A significantly higher EMG activity, ranging from 0.3 to 6.1 times of EMG in walking (~30% to 610%), have been found in the pairs of flexors/extensors of hip, knee, and ankle during TC movements in this study, consistent with that of Wu and colleagues.[38] Tseng and colleagues reported their EMG findings from the vastus lateralis, vastus medialis, bicep femoris, and gastrocnemius muscles during TC and walking in 11 experienced TC practitioners.[21] They found that compared with walking, the EMG activity for the quadriceps and vastus lateralis muscle was significantly greater in TC stepping. Obviously, the findings from the aforementioned two studies and this study supported the conclusion that TC movements generated more active muscle activity in the lower limb than walking.

One limitation of this study was the EMG signal analysis. The average single TC gait cycle in this study was approximately 10 seconds; the duration of a complete static TC movement was 5 seconds while a complete dynamic TC was between 5–15 seconds in length. Owing to this technical limitation, the EMG signals were unable to be collected throughout the entire TC movement, only 5 seconds of EMG signals (half of one gait cycle time of a dynamic TC movement OR the equivalent to one cycle of a static TC movement) for each TC movement was selected for analysis. EMG data from a full TC gait cycle would be remarkably interesting to analyze.

Conclusion

This study examined the joint angles, joint moment, and EMG activity of the lower limb during the performance of seven TC movements and compared them with the measures from walking. Compared with walking, practicing dynamic TC movements required greater joint movement angles of the lower limb; most dynamic TC movements generated larger flexion and abduction joint moment at the joints of the lower limb; and performing TC resulted in higher muscle activity of the lower limb, particularly in the hip abductors and adductors. The hip adductors and adductors have key role in postural stability for all population, particularly for older adults. These TC movements could be a good option for older adults, especially to improve the muscle strength and ROM of their lower limbs.

Submission statement

The manuscript has been published in *Sport Medicine and Health Science*.

Authors' contributions.

Dr. Li contributed to the conception and principal guidance to the study. Mr. Law contributed to the data collection and data processing. Both authors contributed to drafting of the manuscript. Both authors have read and approved the final manuscript.

Ethics approval statement

The study was approved by the human ethics committee of the University of Ottawa. The participant was a volunteer, without a monetary incentive and were informed about the use of their information. Informed consent from the participant was obtained.

Conflict of interest

The authors have no conflicts of interest to report.

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Research article 2

Title

Effects of a biomechanical-based Tai Chi program on gait and posture in people with Parkinson’s disease: study protocol for a randomized controlled trial

Names protocol contributors

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Abstract

Background: Parkinson's disease (PD) is associated with changes in gait and posture, which increases the rate of falls and injuries in this population. Tai Chi (TC) training enhances the movement capacity of patients with PD. However, the understanding of the effect of TC training on gait and postural stability in PD is lacking. This study aims to examine the effect of a biomechanical-based TC training on dynamic postural stability and its relationship with walking performance.

Methods/Design: A single-blind, randomized control trial of 40 individuals with early-stage PD was conducted (Hoehn & Yahr stages 1 to 3). Patients with PD will be randomly assigned to either the TC or control group. The TC group will participate in a biomechanical-based TC training program that is formed based on the movement analysis of TC and will be practiced thrice a week for 12 weeks. The control group will be required to engage in at least 60 min of regular physical activity (PA) on their own for three times per week for 12 weeks. The primary and secondary outcomes will be assessed at baseline and at 6 and 12 weeks after commencing the study protocol. The primary outcome measures will include dynamic postural stability indicated by the center of mass and center of pressure separation distance and clearance distance of the heel and toe measured during fixed-obstacle crossing. The secondary measures are gait speed, cadence, step length during level surface walking (simple task) and fixed-obstacle crossing (challenging task). The Unified Parkinson's disease Rating scale, single leg-stance test with eyes open and closed, and three cognitive scores (Stroop Test, Trail Making Test- Part B, and the Wisconsin Card Sorting Test) were also employed.

Discussion: This protocol could lead to the development of a biomechanics TC training program for the improvement of gait and postural stability among individuals with PD. The program could enhance the understanding of the effect of TC training on gait and postural stability and could help improve or preserve the postural stability, self-confidence, and active participation in social activities of the participants, thus enhancing their overall quality of life.

Trial registration: ClinicalTrials.gov (*registry*), NCT04644367 (*registration number*), November 25, 2020 (*date of registration*).

Keywords

Parkinson's disease, Gait, Postural stability, Falls, Tai Chi.

Administrative information

Note: the numbers in curly brackets in this protocol refer to SPIRIT checklist item numbers. The order of the items has been modified to group related items (see http://www.equator-network.org/reporting-guidelines/spirit-2013-statement-defining-standard-protocol-items-for-clinical-trials/).

Title {1}	Effects of a biomechanical-based Tai Chi program on gait and posture in people with Parkinson's disease: study protocol for a randomized controlled trial
Trial registration {2a and 2b}.	NCT04644367, ClinicalTrials.gov
Protocol version {3}	2020-2-19. Version 1.

Funding {4}	This study was not supported by any funding.
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Name and contact information for the trial sponsor {5b}	This trial was supported by the University of Ottawa.
Role of sponsor {5c}	The sponsors did not play a role in the design of the study and collection, analysis, and interpretation of data and in writing the manuscript.

Background and rationale {6a}

Parkinson's disease (PD) is a growing concern in Canada, where approximately 100,000 people are living with PD; this number is expected to rise to 163,700 by 2031 [1]. The direct and indirect socioeconomic costs in Canada associated with this neurological condition is estimated to be more than $1.214B per year [2]. Postural instability and gait difficulties are common problems reported among people with PD [3,4]. People with PD have difficulties with daily tasks such as walking caused by gait-related changes in step width and step length that can lead to reduced walking speeds [5,6]. This "cautious gait" approach is similar to older adults who are at an elevated risk of falls [5,7]. Falls and the loss of ability to live independently are among the key concerns of people with PD. A one-year follow-up study among 109 subjects with idiopathic PD diagnosed according to the brain bank criteria reported fall occurrence of 68.3% [8].

Exercise intervention programs are being used in conjunction with drug therapy (such as Levodopa, carbidopa) as standard of care to manage the symptoms related to PD [9,10]. Tai Chi (TC) is a body-mind exercise that has been recommended by *Parkinson's Canada* as one of the few exercise programs specific for those with PD [11]. TC training is suggested to help improve the awareness of whole-body movement and joint proprioception and increase muscle strength and endurance of the lower limb, thus strengthening the neuromuscular reaction of muscles in the lower extremities [12,13]. For people with PD, TC training would help in challenging postural stability, particularly in the mediolateral (M-L) direction that is closely related to fall prevention. It will also strengthen the muscles at the hip involved in postural control. Regular TC practice and training would lead to improvements in gait and postural stability by encouraging weight shifting, control displacement of the COM over the base of support, and comfort with stepping in different directions.

Objectives {7}

Several TC studies for PD have been published [14-22]. However, details about how TC programs were formulated or how TC forms were selected are unknown. This missing information may affect the training effect because TC has many forms and has unique styles. Moreover, the effect of TC training on dynamic postural stability and how it relates to walking performance and challenging walking, such as obstacle crossing, is unclear. This information gap is important for people with PD because their dynamic postural stability is challenged. This study aims to examine the impact of a biomechanical-based TC program training on gait and postural stability, particularly on dynamic postural stability and how it relates to walking performance and obstacle crossing. Based on our previous studies [12, 23, 24], it is hypothesized that a biomechanical-based

TC program training will help in improving gait and dynamic postural stability by increasing walking speed, stability in M-L direction, and toe and heel clearance distance during obstacle crossing in the individuals with PD. This protocol could lead to the development of an innovative balance and gait training program tailored to individuals with early-stage PD.

Trial design {8}

A single-blind randomized control trial will be conducted to compare the effects of a TC program with a physical activity (PA) routine (Figure 3.1). The study will be conducted for 12 weeks (3 months), and this period will include a 12-week intervention period with primary and secondary outcomes measured at baseline and at 6 and 12 weeks.

Study setting {9}

University of Ottawa's Human Movement Biomechanics Laboratory will serve as the primary site for the study. TC interventions will be offered at the community centers in Ottawa, Canada. The PA routine can be performed inside or outside the home environment.

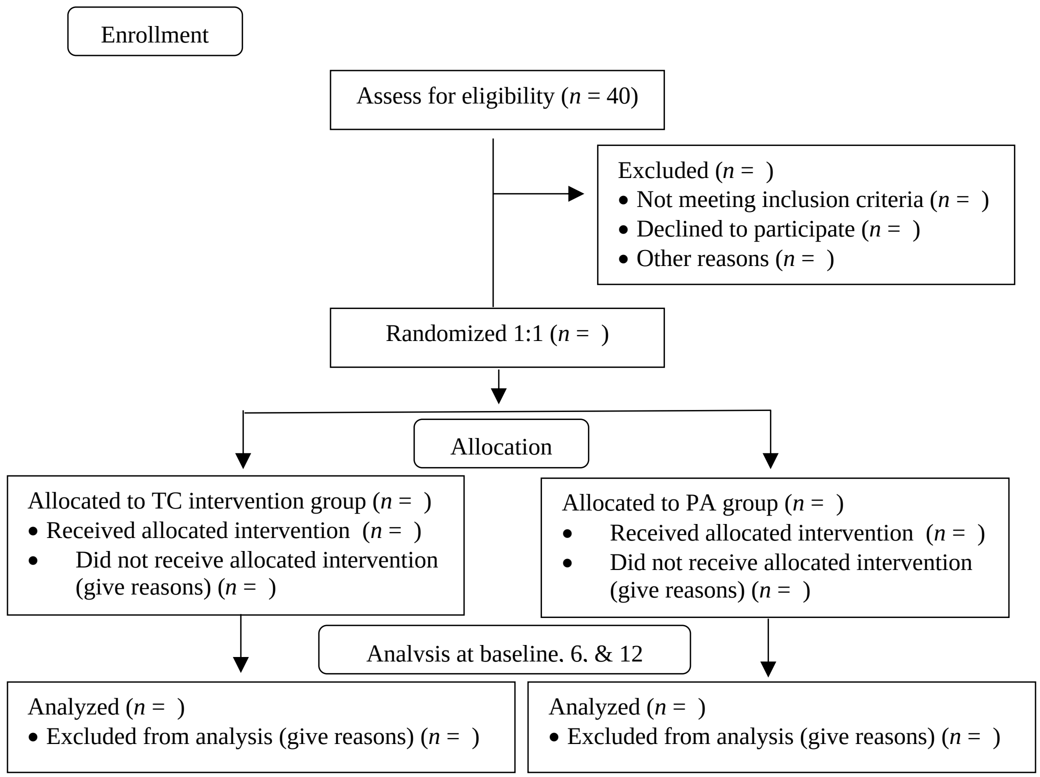

Figure 3.1. Flow diagram of TC study with design and illustration of experimental and control

Eligibility criteria {10}

Participants will be included in the study if they meet the following criteria:

1. Have been diagnosed with PD and demonstrate a disease severity ranging from 1 to 3 on the Hoehn and Yahr (H&Y) scale;
2. Have no fluctuations in motor symptoms (i.e., “wearing off effects” or end-of-dose deterioration 2–4 after a dose of Levedopa) as reported by the motor section of the Unified Parkinson’s Disease Rating Scale (UPDRS-III);
3. Have stable PD and doctor-prescribed medication use (such as levodopa or carbidopa), that is, fluctuation did not occur at the time of medication intake;
4. Can stand and walk independently;

5. Available thrice a week over a period of 12 weeks; and
6. Be able to engage in PA for at least 60 min on their own, thrice per week, without prior experience practicing TC regularly.

Participants will be excluded from the study if any of the following conditions are reported:

1. Enrolled into any other behavioral or pharmacological studies;
2. Have a Montreal Cognitive Assessment (MoCA) score of < 26/27 (that indicate some mild cognitive impairment (MCI)) [25];
3. Have had a serious medical condition or uncontrolled hypertension (equal or greater than a systolic 180 or diastolic 110 reading);
4. Have any debilitating conditions that could prevent them from performing any PA for a minimum of 60 minutes; and
5. Have practiced or have experience of practicing TC in an organized class or program within the last 5 years at the start of participation in the study.

Who will take informed consent? {26a}

The primary investigator will obtain informed consent from the potential trial participants.

Additional consent provisions for collection and use of participant data and biological specimens {26b}

No secondary participant information or data will be collected, nor any biological specimens will be collected.

Interventions

Explanation for the choice of comparators {6b}

The two comparators are the TC intervention and PA group (control group). The two comparators were chosen to understand the effect of 12-week biomechanical-based TC training on the gait and posture of people with PD compared with those who will maintain their regular PA. An active PA (control) group was chosen for avoiding an unfair comparison to participants who are sedentary or who are inactive.

Intervention description {11a}

TC program development

The biomechanical-based TC training program has been developed based on research with an experienced TC master, our previous work, and by biomechanical analysis of TC movement. Seven TC movements were chosen based on the following considerations:

5. Easy to learn;
6. Feasible to practice;
7. Can be practiced either individually or in groups;
8. Space requirement is minimal (e.g., practicing inside the home, living room, or yard);
9. The seven selected TC movements and the three static and four dynamic forms are listed in Table 3.1. A static TC movement was defined as the movement in which the center of mass (COM) was maintained within the limits of the body's base of support (BOS), whereas a dynamic TC movement was defined as the movement, in which the body's COM was outside the limits of the body's BOS. Figure 3.2 illustrates three dynamic TC movements from the seven TC movements. These TC movements are typical TC movements and are present in all classic TC styles, such as Wu, Yang, and Chen styles [26]. The biomechanical analysis of the seven selected TC movements in terms of their kinematics, kinetics, and muscle activities demonstrates their unique features compared with walking. These movements require increased foot clearance, step length, and movement in the backward, sideway, 45-degree angle, and forward directions [23,27].

Regular performance of these movements would result in special training to postural control, particularly in the adductor and tensor fasciae latae muscles that are responsible for maintaining M-L postural stability and assisting in preventing falls [23,24]. TC training can help in challenging M-L stability through shifting of the body's COM, using the full range of motion of joints, and increasing step width [23,24]. Electromyography activity while performing the seven TC forms has revealed higher activation of the hip adductor muscles compared with walking, this could train the muscle to prevent lateral falls [26].

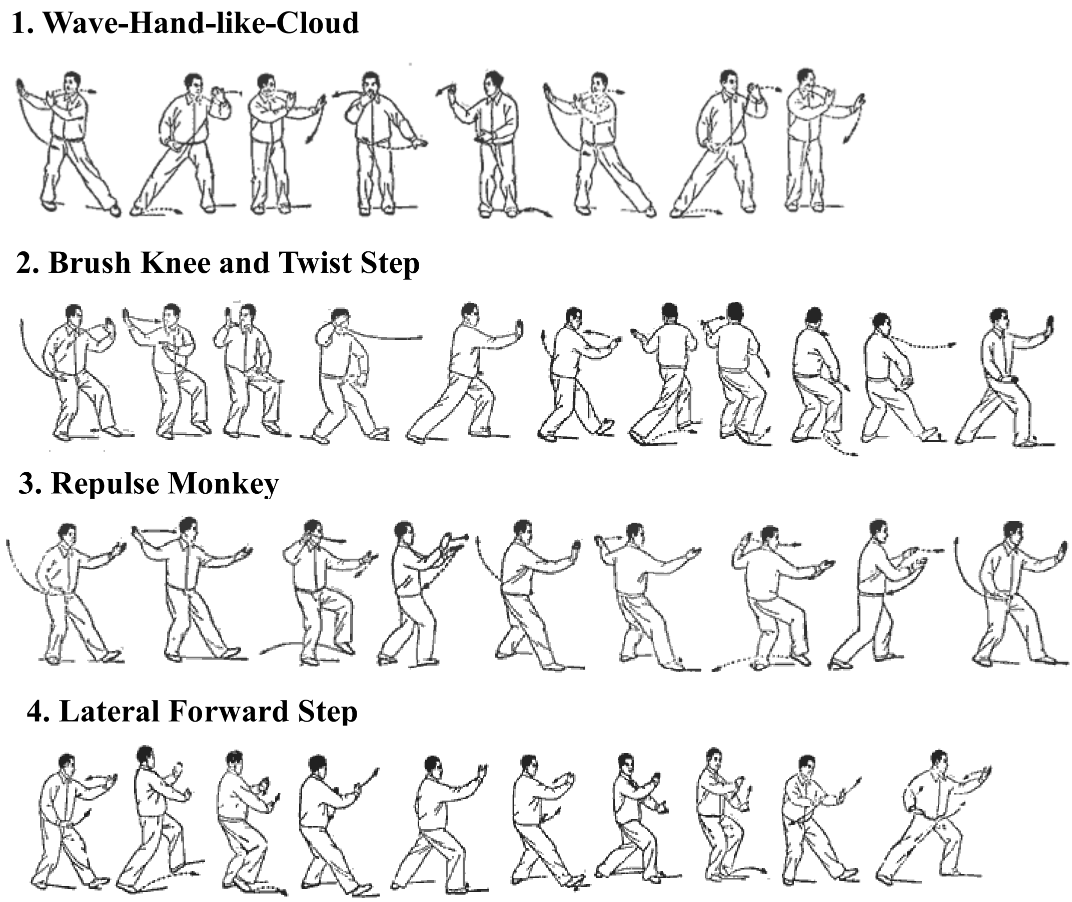

Figure 3.2. Illustration of four dynamic forms from the proposed 7-form TC program (images from "*Simplified Tijiquan*" published by the CHINA SPORTS Editorial Board, Fifth Edition 1990, Beijing China).

Table 3.1. Seven-form TC program for people with PD.

TC form	Characteristics
Form 1: Starting Form	Standing (arms): arms from down to up
Form 2: Hero Lift the Sky	Standing (arms): push up to down
Form 3: Standing, push hand back	Standing (arms): neutral to back
Form 4: Wave-Hand-like-Cloud	Sideway stepping: left and right
Form 5: Brush Knee and Twist Step	Forward Diagonal stepping: left and right
Form 6: Repulse Monkey	Backward Diagonal stepping: left and right
Form 7: Lateral Forward step	Lateral Diagonal stepping: left and right

TC training group

For the TC group, the first two weeks of the program will require the participants to work on some light breathing and simple upper limb forms. The basic TC forms will be introduced with a focus on becoming comfortable with the flow and rhythm of the movements. Each session will run for 60 min and will be supervised by a TC instructor in a community center. The training will be gradual and range from low to moderate intensity. Participants will warm up for 5–10 min, perform core activities for 40 min, and cool down for 5 min. Three sessions will be offered weekly for 12 weeks; the participants will be asked to attend at least two sessions weekly. The third to sixth week of the program will focus on incorporating the upper- and lower limb into the routine. These classes will focus on practicing the seven TC forms sequentially. The six remaining weeks of the program will focus on repetitions and performance proficiency in the basic seven-form routine. The participants will be allowed to practice TC at home. Any TC that the participant performs in their home or on their own time will be recorded by themselves by using a monitoring form that will be distributed to them and collected weekly. The TC instructor will be present at each of the session to monitor the participants' progress and to ensure that the movements are being performed correctly.

Physical activity group

The PA group will track their level of PA over 12 weeks. During this period, the participants will be required to engage in at least 60 min of regular PA on their own for three times weekly. Regular PA may include walking, cleaning, performing chores inside the home, and/or climbing the stairs. No restriction will be made to limit others forms of PA. Individuals in the PA group will be permitted to engage in organized sports and instructor-led class such as boxing and dance to ensure that the participant recruitment process is feasible. An active control group was used for comparisons between the groups who will or will not receive formal TC training and to reflect the daily lifestyle and activities of a typical individual with PD from the community. Similar to the TC group, the participants in this group will be asked to complete an activity log form for monitoring, and this form will be collected weekly to monitor their regular PA levels.

Criteria for discontinuing or modifying allocated interventions {11b}

At any point during the study, either the intervention period or laboratory testing sessions, the participants will be free to refuse to participate. If he or she chooses to participate, the participant may withdraw from the study at any time for any reason.

Strategies for improved adherence to interventions {11c}

For the group receiving the TC intervention, three class sessions will be offered weekly for 12 weeks. The participants will be asked to attend three sessions weekly. These classes will be monitored by the PI and TC master. This set-up will ensure that the classes are offered at a flexible time for the participant that match their availability and schedules. The participants of the PA group will be asked to maintain regular PA levels and complete an activity log form for monitoring. This form will be collected weekly to monitor their regular PA levels to ensure that they will be motivated and consistent in their PA engagement and performance.

Relevant concomitant care permitted or prohibited during the trial {11d}

No concomitant care and interventions requirements are either permitted or prohibited during the trial. The participants will be asked to maintain their medication dosage and any mandatory medical care or aid that they are receiving during the intervention period. To encourage engagement and enrolment into the study, we allowed the TC and PA groups to engage in forms of exercise and PA, and no restrictions will be made, because this set-up will not affect the outcome or results of the study.

Provisions for post-trial care {30}

n/a

Outcomes {12}

All outcome measures will be conducted by the researchers, blind to group allocation, after 1 week (baseline), 6 weeks (mid-intervention), and 12 weeks (post-intervention). The demographic information of the participants, including age, sex, and clinical information such as stage of PD and medication reported will be collected from the participants.

Primary outcome measures

Dynamic postural stability

1. COM-COP separation distance in the anterior-posterior (A-P) and M-L directions. The separation distance of the body's COM and COP will be determined through motion

analysis of walking and obstacle crossing trials to reflect the body's dynamic postural stability.

2. Clearance distance of the toe and heel. The clearance distance of the toe and heel will be measured from position of the foot to the height of the obstacle during obstacle crossing. This parameter indicates the dynamic postural stability.

Secondary outcome measures

Gait performance

I. Gait speed. This is a measure of how quickly an individual can walk within a specified distance. Gait speed is a global measure of functional capacity, mobility, and movement performance.

II. Cadence. This measure is defined as the total number of full gait cycles that is completed over a period. In human movement analysis, this gait cycle is defined as the repeated instances of subsequent foot contacts of the same foot. Analysis of cadence variability can reflect the individual's movement capacity and their body's ability to maintain rhythmicity during movement.

III. Step length. This measure is defined as the distance travelled by a person over one cycle from the initial heel strike to the next heel strike.

Clinical and cognitive (Executive Function) assessment

1. Unified Parkinson's Disease Rating Scale- motor examination (UPDRS-III). UPDRS-III is a standard clinical assessment tool for the evaluation of the severity and progression of the motor-related symptoms of PD. This scale has 14-items, each scored on a 5-point Likert

scale ranging from 0 to 4, with 0 representing “no impairment” and 4 representing “marked impairment”.

2. Single-leg stance test with eyes open and closed. The participant will be asked to stand for as long as possible up to 60 s with either eyes open or closed. Trials will be terminated if the participant loses his or her balance, or if his or her feet move from the initial position. The sequence of the eyes open or closed trials will be randomized. Three trials per eyes open and eyes closed condition will be performed with 3-min rest in between. This set-up was used, because this test can be used to reflect the muscle strength of the lower extremities and to test static postural stability [28].
3. Timed Up and Go Test (TUG). The individual will be instructed to stand up from a chair, walk 3 meters as quick and safely as possible, cross a line marked on floor, turn around, walk back, and sit down. The individual will be permitted to use the chair’s arm or back support for assistance when standing up, if needed [29]. The time from the “go” signal until the completion will be recorded. This test aims to measure the functional mobility used in the clinical setting.
4. Trail Making Test Part B (TMT-B). The participants will be given a set of numbers and letters that they will be asked to connect with lines the numbers to letters in ascending order. The time consumed by the participant to complete this task will be recorded. TMT-B was used to measure processing speed and mental flexibility [30] and as a screening tool for neurological deficits such as MCI [31].
5. Wisconsin Card Sorting Test (WCST). The participants will be given a deck of 64 cards and will be asked to sort the cards by shape, color, or number. The number of errors made, and the number of successful sorted categories (maximum of 6) will be recorded.

Participants will receive feedback whether the card sorted is "correct" or "incorrect"; after completing 10 consecutive sorts, the participants will switch to the next sorting category, and this process will be repeated until all the cards in the deck have been sorted. This method is frequently used as a measure of mental switching and response preservation [32].

6. Stroop Test. The participants will be asked to name the color but not to read the word on a card. A color-word score will be given based on the total correct identification of the correct color within 45 s. The Stroop Test is a measure of how the brain process interfering signals. This test measures attention, inhibition control, and response inhibition [32,33].

Participant timeline {13}

Figure 3.3. Schedule of enrolment, intervention, and assessment for proposed TC intervention study involving those with Parkinson's disease.

	STUDY PERIOD					
	Enrolment	**Allocation**	**Post-allocation**			**Close-out**
TIMEPOINT -t1 = Jan 2021 t1 = May 2021 t2 = Jun 2021 t3 = Jul 2021 tx = Dec 2021	$-t_1$	**0**	t_1	t_2	t_3	t_x
ENROLMENT:						
Eligibility screen	X					
Informed consent	X					
Allocation		X				
INTERVENTIONS:						
TC training			◆————	————	————◆	
Regular PA			X		X	

ASSESSMENTS:						
Demographic details and background	X	X				
Gait and Dynamic Postural Stability parameters			X	X	X	
Clinical assessments			X	X	X	
Cognitive Assessments			X	X	X	
Exit Questionnaire						X

Sample size {14}

The estimated number of participants to achieve the study's objectives is 40, calculated to attain a 93% statistical power in the difference between two independent means testing hypotheses with an alpha level of 5%. This estimation is based on the calculation of the minimal clinical important difference (MCID) that were determined based on the values obtained in past published studies for the variables stride length and COM-COP separation [15,34–36]. The MCID is the representative value of the smallest change for an outcome measure to be deemed or perceived as being beneficial. Considering a 10% of dropout rate of the participants recorded from a previous 24-week TC intervention study for those with PD [15], a 10% dropout rate is expected.

Recruitment {15}

Participants with PD will be recruited in the city Ottawa and greater Ottawa area, Ontario. All participation in the TC intervention and PA routine will be on the basis that the first randomly allocated 20 participants will be considered for participation in each group. The recruitment of the participants will be obtained through three sources as follows: (1) referrals from local medical clinics (i.e., physician or neurologist offices); (2) local Parkinson's support groups associated with *Parkinson's Canada*; and (3) bulletin board, newsletters, or postings in the hospital.

Assignment of interventions: allocation

Sequence generation {16a}

Potential participants will be screened on the telephone by a research assistant. Participants who are willing and eligible to participate will be randomly assigned in a 1:1 ratio to TC group or PA group by using a concealed block-randomization procedure, stratified by age and sex.

Concealment mechanism {16b}

The block randomization design will use permuted block sizes of 4 and 6 with the participant assignments placed in opaque, sealed, and serially numbered envelopes and individualized for each participant.

Implementation {16c}

The randomization schedule will be generated by the data analyst, who will deliver this document in a sealed envelope to the research assistant responsible for assigning the participants to the two groups.

Assignment of interventions: Blinding

Participants to be blinded {17a}

Changes in the participants' gait and postural stability and cognitive performance will be evaluated based on their individual pre-intervention scores. This process will ensure that the effects of the two intervention programs are examined instead of the differences in the individual performance or expectations of the participants. The intention and goals of the study will be fully disclosed at the end of the participants' intervention period.

Procedure for unblinding if needed {17b}

n/a

Data collection and management

Plans for assessment and collection of outcomes {18a}

A 10-camera Vicon motion analysis system (two Vicon Vantage and eight Vicon Bonita optical cameras, Oxford Metrics, Oxford, UK) with a sampling rate of 200 Hz will be used to capture the participants' gait and obstacle crossing. Prior to data collection, 45 reflective markers (14 mm diameter) will be placed on the participants' body landmarks according to a modified Helen Hayes marker set. Ground reaction forces will be collected using four force plates recorded at 1,000 Hz (two Kistler models: Kistler Instruments Corp, Winterthur, Switzerland; two Bertec models: Bertec Corporation, Columbus, OH, USA). The force plates will be embedded in the middle of an 8 m-long walkway. The participants from the TC and PA (control) groups will be required to visit the University of Ottawa's Human Movement Biomechanics Laboratory on three laboratory sessions at baseline and at 6- and 12-weeks post-intervention. The data collection session will consist of preliminary screening questionnaire, gathering of anthropometric data, 3D motion capture during obstacle crossing and walking, and neuropsychological assessment of executive functioning.

3-D motion capture:

1. Gait performance test: Participants will be asked to walk along an 8 m-long walkway at their self-selected comfortable speed during which their movement will be recorded using

3D motion capture for the analysis of their 3D kinematics and kinetics characteristics of the gait. Walking performance will be used as a baseline condition for comparison with obstacle crossing, because it is a simple task to perform and can provide some indications to the participants' overall health and functional status. Five successful walking trials will be collected.

2. Obstacle crossing test: Participants will perform obstacle crossing in the laboratory for the analysis of their dynamic postural stability and gait performance. An obstacle composed of two upright upholders and a crossing plank with a height of 20 centimeters (cm) will be placed in the middle of the walkway, where the force platforms are embedded. This plank has been made easily collapsible to keep the participants safe to prevent fall. Five successful obstacle crossing trials will be collected.

Neuropsychological Assessment:

The three following neuropsychological assessment tools was used to examine executive functioning: Trail Making Test Part B (TMT-B), Wisconsin Card Sorting Test (WCST), and Stroop Test. These three neuropsychological assessments tools are commonly used to measure executive functioning in aging research and have been recommended as popular screening tool for the assessment of mild cognitive impairment [36,37].

1. TMT-B: participants will be provided with a set of numbers and letters and will be asked to connect a line from a number to a letter in ascending order. The time that it takes the participant to complete this task will be recorded.
2. WCST: participants will be given a deck of 64 cards and will be asked to sort the cards according to shape, color, and number. The number errors made, and the number of successful sorted categories (maximum of 6) will be recorded. Participants will receive

feedback about sorting the cards as “correct” or “incorrect”. After completing 10 consecutive sorts, the participants will switch to the next sorting category and this repeated until all the cards in the deck have been sorted.

3. Stroop Test: participants will be asked to name the color but not to read the word on a card. A color-word score will be given based on the total read in 45 seconds.

For the 3-D motion capture, the data will be collected and analyzed using Vicon’s *Nexus* software (v. 2.8.1) and tabulated in MATLAB (v. 7.1. Release 2006a) to obtain the temporal and spatial parameters. The functional and neuropsychological assessment measures will be gathered and stored both as hard and digital copies for further data interpretation and analysis. Descriptive analysis of the movements will be first conducted. The completion of all trials will be checked, and missing trials will be checked. For the 3D motion capture data of the participants’ movement, the data will be digitized, filtered, and processed. All *Nexus* software calculations will be derived from the Plug-in-gait model (Vicon Oxford Metrics, Oxford, UK). For each trial that will be collected, the data will be normalized to one full gait cycle. One gait cycle is defined as the succession of repeated foot-strike to the next foot-strike of the same foot. The primary outcomes will be normalized by the participants’ body height and weight.

Plans to promote participant retention and complete follow-up {18b}

Participants in the TC group will be asked to partake in three 1-hour TC class weekly for 12 weeks. This duration and frequency of practice has previously been used in past TC studies for this population to achieve the desired beneficial effects on postural stability and movement capacity [15,16]. The selected intensity, duration, and frequency of the training is appropriate to meet the demands of a low-to-moderate level of exercise classification.

To mitigate any feelings of physical discomfort or muscle fatigue, we will instruct the participants to warm up prior to the training and perform each TC form at their preferred comfortable speed. The participants will be allowed to rest or take breaks when they prefer. Based on our previous conducted research in TC biomechanics and intervention, practicing TC is safe to seniors [23,24,26,38]. However, a participant that feels any discomfort may withdraw from the study at any time for any reason.

The safety of the participants in the community center and laboratory settings is a primary consideration. At all times during training session or laboratory testing, both the TC instructor, PI, and/or a research assistant(s) will be present to monitor the performance and abilities of each individual participant. Participants who are deemed to be at risk of falling will be provided with a spotter, who will ensure the safety of the participant. Monitoring by the PI, instructor and/or research assistant will help to prevent accidental trips and falls. During the TC session, the participants' progress in the TC program will be monitored. To encourage compliance in the program, the PI will confer with the participants' daily activity log of their TC practice to see if they are achieving the weekly goals and objectives for the class.

Data management {19}

The data, which include the completed informed consent form, testing notes, electronic and printed testing data, will be carefully filed and securely stored in the researcher's office at the University of Ottawa. The computer in the researcher's office will also be locked to limit the access. The data will be encrypted and stored in the password-protected and -encrypted computer of the researcher. The computer will be locked to limit the access. A number code system will be employed during the data collection, analysis, and reporting. In addition, only the researchers can access the number code system in relation to the data obtained from the participants (e.g., electronic data, the master sheet). The master sheet that links the participants' identification to their number code and other data documents will be kept in a locked filing cabinet of the PI’s office.

Confidentiality {27}

Information from the study will be held in strict confidentiality and will not be used except for research purpose. The information collected in the study will be coded with anonymity. Any published results will be presented with complete anonymity. Any personal (e.g., address and telephone number) and testing data will be kept in a separate file folder, accessible only by the researchers responsible for the project. The data will be conserved for a period of 5 years after the time of publication. After the time of publication, all the electronic data will be permanently deleted from the computer. The printed data file will be shredded.

Plans for collection, laboratory evaluation and storage of biological specimens for genetic or molecular analysis in this trial/future use {33}

n/a

Statistical methods

Statistical methods for primary and secondary outcomes {20a}

Statistical analysis will be performed using SPSS 20.0 and Microsoft Excel 2019 software. Each of the measures will be expressed as mean ± standard deviation. If a measure is not normally distributed, bootstrap method will be applied before the mean ± standard deviation values are reported, as well the confidence interval. The participants’ data from the TC and PA group will be split by gender (i.e., male or female) and by age (i.e., within ± 10 years). Two equal-sized, subsampled groups from the larger dataset will be obtained while keeping the statistical power of comparison above 80%, which can be achieved by recalculating the statical power in G*Power following the redistribution by gender and age in each group. Analysis will be performed to the measures obtained from baseline and at 6 and 12 weeks after TC training. Then, the data between the TC & PA groups will be compared. Two-way analysis of variance (group × time) with repeated measures will be used for examining the effect of TC training on the primary and secondary outcomes. The participants will be analyzed based on their initially allocated groups via randomization, regardless of whether they adhere or if they received the allocated intervention. Statistical significance will be set at P less than 0.05.

Interim analyses {21b}

n/a

Methods for additional analyses (e.g., subgroup analyses) {20b}

No planned subgroup analyses were involved in this study. Gender differences are anticipated to be present, but these differences are not one of the primary outcomes of interest or one of the effects of TC training. We do not anticipate any gender effects to remarkably contribute to the effects of TC training. Efforts were made to ensure that only the effects of TC training are examined, by making the intervention groups comparable, setting a strict age-range for the participants' age, and using the individual's baseline scores for comparisons with their post-training evaluations. Accordingly, we will strictly examine the potential mechanisms and training effects of TC for symptoms related specifically to PD.

Methods in analysis to handle protocol non-adherence and any statistical methods to handle missing data {20c}

All data will be thoroughly checked for completeness. Should data be missing from any of the gait or obstacle crossing trials, every effort will be made to locate it first before those cases with the missing data will be dealt with using multiple imputation and analyzed with this adjustment (complete-case analysis).

Plans to give access to the full protocol, participant level-data and statistical code {31c}

Public access will be granted to the full protocol, participant-level dataset, and statistical code upon request.

Oversight and monitoring

Composition of the coordinating center and trial steering committee {5d}

The thesis (or steering) committee of the PhD candidate, who will be responsible for conducting and overseeing this study, will guide and provide feedback to develop and refine the details of the study. The thesis committee includes Drs. Denis Prud'homme and Youlin Hong. This committee will ensure that the quality of the candidate's work meets all academic regulations and requirements for completion of the candidate's degree. The committee will review the candidate's work for publications, travel applications, and application funds to conferences and seminars.

Composition of the data monitoring committee, its role and reporting structure {21a}

A data monitoring committee is not needed, because this role will be fulfilled by the thesis (steering) committee.

Adverse event reporting and harms {22}

Participants will be allowed to take breaks or rest whenever they prefer. If the participants feel physical exerted, they will be allowed time to rest and water or other forms of rehydration methods would be provided to them. Prior to the performance of the TC routine, the participants will go through a proper warm-up that will involve some basic (light) stretching, breathing, and warm-up movements for the upper and lower extremities. This activity would help mitigate any undesired muscle fatigue, discomfort, or soreness. To reduce the risk of falls or related injuries, the TC instructor, and/or the researchers will be available to monitor the performance of each participant. For participants that are deemed at a higher risk of falling, a spotter will be provided upon either request by participant or if it is evident to the instructor/PI that a spotter is needed. All serious injuries/harm resulting from either the laboratory testing or TC intervention, PA engaged by the participants will be reported to the PI and Research Ethics Board (REB) of the University of Ottawa.

Frequency and plans for auditing trial conduct {23}

Frequency and plans for auditing trial conduct will not be conducted unless required by potential funding agencies.

Plans for communicating important protocol amendments to relevant parties (e.g., trial participants, ethical committees) {25}

Considering the recent COVID-19 situation, any important protocol modifications to the investigators, REB, trial participants, trial registries, journals, and steering committees will be communicated accordingly.

Dissemination plans {31a}

This research protocol could lead to the development of an innovative balance and gait training program that is tailored to individuals with PD. Other training or exercise programs can be modelled from the proposed research protocol in addition to aid, assist, or guide healthcare professionals or therapist in their development or design intervention programs for PD. By examination of the biomechanics of challenging locomotion, obstacle crossing, and TC training impact on gait and posture in the population, it could add understanding to the mechanisms of TC training. This research will help guide the development of more effective exercise programs for health promotion and fall prevention that is not restricted to the target population alone. The work outputs may contribute to multiple publications, conference submissions, and information sessions in support groups for those with PD. This work will satisfy the requirements of a PhD degree in Human Kinetics.

Several types of exercise intervention programs have been developed with limited effectiveness towards treating the movement symptoms related to PD, namely gait disorders and postural instability. Resistance training can help improve strength after a 10 to 12-week period [39,40], but only in certain groups of muscle and are ineffective towards training overall postural control and balance. Considering the heterogeneity of the intervention and study outcomes used in these resistance training studies [41], the associated risks of injury, increased level of intensity, and longer duration of resistance training programs required to improve posture and gait are problems for those with PD. Treadmill training for 12 weeks showed an improvement in walking distance [34]. However, the operational costs needed for a body-harness or specialized equipment, assistance from a trainer or physical therapist make this form of training not feasible as a long-term option to manage PD. Balance-specific training programs cannot improve all aspects of balance or reduce the risk of falls, mainly because these programs rely on different exercises and activities to retrain balance and posture, with varying levels of effectiveness [42,43]. Strength, balance, and coordination are some aspects of postural stability that need to be improved, but such programs for PD need to be overly complex and include several multi-modal exercises.

TC, as a "mind-body" exercise, has been applied to manage PD-related symptoms and has increased in popularity because of its rehabilitative potential. TC training shares many features as rhythmic exercises such as tango and ballroom dance that focus on the timing of the participant's foot placement, whole body coordination, and awareness and attention to their own and partners' movement [44]. TC is a form of martial art that has been recommended by the *American Geriatric Society* and *British Geriatric Society* for fall prevention in the elderly [45]. However, these activities are only general recommendations that are provided without the proper training protocols and guidelines for those with PD who wish to use TC as a form of therapy or exercise to maintain their physical health and wellbeing. Previous TC programs for PD have demonstrated beneficial effects on posture, gait, and mobility, but limited information is available about the selection basis of TC movement. The mechanisms in the beneficial effects of TC training on gait and postural stability for the people with PD is unknown. MRI results have provided support to the beneficial effects of TC practice on brain structure and cognition function [46]. More research on TC intervention on gait, postural stability, and cognition function would improve the understanding of the effects of practicing TC in PD and to access its role and safety as an effective form of exercise to improve quality of the life of this population.

The proposed study protocol is unique and novel, because firstly it is specifically and purposefully designed for PD people for improving their postural stability and gait performance. Furthermore, the biomechanics characteristics of seven TC movement have been understood that forms a foundation for the understanding of the mechanism of TC training. Lastly, with the future development of multimedia materials, tablet, and mobile phone APP's, the TC intervention program would become more feasible and practical. This protocol could lead to the development of an original and innovative balance and gait training program that could help individuals with PD. The 3D biomechanical analysis of the gait and obstacle crossing in the two groups will enable us to understand the effect of TC training on movement and postural control and how this relates to walking performance and obstacle crossing. This study can serve as model for healthcare professionals or therapists when designing or developing future intervention programs for PD. The information obtained from the biomechanical analysis of gait and posture in the population would enhance our understanding of the effects of exercise on PD and how to apply exercise in management of PD.

One possible limitation of the study is that although TC has been gentle on the body, participants with PD may have difficulties following all demonstrations and instructions from the TC instructor. The participants are expected to achieve the necessary level of intensity and duration that would normally be experienced during a light to moderate-intensity exercise. However, their underlying physical and health conditions will need to be carefully monitored by the TC instructor at each TC session. The participants' progress will be tracked by the researchers, but they will not be challenged beyond their physical and mental limits during practice.

In conclusion, the proposed study will improve the understanding of the effects of TC training among those with PD by using a biomechanical analysis to explain the potential changes in postural stability and gait. The knowledge about the effects of TC training, particularly in gait, postural stability, and cognition, would provide an exercise option for the management of PD and improve the quality of life of this population.

Trial status

This study is in the initial stages of planning as of Aug 2019. Application of the human ethics approval has been submitted and approved as of Oct 2019. Participant recruitment began in Oct 2019. The study will start May 2021 and will be completed by Dec 2021.

Abbreviations

A-P: Anterior-posterior; COM: Center of Mass; COM-COP: center of mass and center pressure; COP: Center of Pressure; H&Y: Hoehn and Yahr; MCI: Mild Cognitive Impairment; M-L: Medial-lateral; MoCA: Montreal Cognitive Assessment; PA: physical activity; PD: Parkinson's disease; TC: Tai Chi; ROM: Range of Motion; SLO: Single-leg stance test with eyes open; SLC: Single-leg stance test with eyes open closed; TUG: Timed Up and Go Test; TMT-B: Trail Making Test Part B; UPDRS-III: Unified Parkinson's Disease Rating Scale- motor examination; WCST: Wisconsin Card Sorting Test; 3-D: three-dimensional.

Declarations

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Authors' contributions {31b}

J-XL contributed to the conception of the trial. J-XL, QZ, and NL contributed to the design of the trial. J-XL and NL contributed to the drafting the manuscript. J-XL, and NL contributed to the refining and submission of the manuscript. All authors have read and approved the final manuscript.

Funding {4}

There is no funding to acknowledge.

Availability of data and materials {29}

The PI will have access to the final trial dataset, there are no agreements that may limit such access for the investigators.

Ethics approval and consent to participate {24}

This study was approved by the Health Sciences REB of the University of Ottawa (Ethics File Number: H-01-19-2284).

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Research article 3

Gait and dynamic postural stability during obstacle crossing in the individuals with early-stage Parkinson's disease

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Abstract

Altered gait and postural stability can lead to a greater risk of falls and injuries in people with Parkinson's disease (PD). The purpose of this study was to examine the gait and dynamic postural stability differences between PD (n = 16, Hoehn & Yahr stages 1 to 2) and age-matched healthy older adults (HOA) (n = 16). The participants' obstacle (20 cm height) crossing motion was captured using a 10-camera Vicon motion system. Gait parameters, toe and heel clearance distance, pre- and post-horizontal distance, displacement and velocity of center of mass (COM), COM-center of pressure (COP) separation distance were analyzed along with the timed up-and-go test, single leg stance (SLS). Individuals with PD spent a significantly shorter time in SLS with eyes open or closed compared to the controls ($p < 0.05$). During obstacle crossing, they walked slower, with significantly smaller hip flexion angle (48 ° vs. 52 °, p = 0.024) and larger knee adduction angles of the trailing limb (29 ° vs. 39 °, p = 0.028), larger mediolateral COM displacement and COM-COP separation distance compared to the HOA. The altered postural stability suggests more attention should be paid to avoid injury or fall in this population.

Keywords: fall, movement disorder, kinematics, joint angles, range of motion.

Word count: 3040.

Introduction

Postural instability and altered gait contribute to a higher rate of falls and injuries among people with Parkinson's disease (PD). Approximately 45% to 68% of individuals with PD have experienced at least one fall within a one-year period.[1–3] Biomechanical changes in gait and postural stability have been reported in this population.[4–6] Postural stability refers to the ability to control the body position in space.[7] **Static postural stability** refers to the ability to maintain steadiness on a fixed, firm, and unmoving base of support (BOS).[8,9] When moving, **dynamic postural stability** refers to the ability to transfer the vertical projection of the center of gravity (COG) around the supporting base.[8] The single-leg stance (SLS) or tandem stance tests showed that PD individuals perform more poorly than heathy people.[10,11] Individuals in the middle stages of PD (Hoehn & Yahr (H&Y) 2.5-3) show increased mediolateral (ML) sway of their center of mass (COM) and center of pressure (COP) while standing.[12–15] Moreover, changes in direction-specific postural stability were found.[16] When standing on a moving platform, PD individuals show increased anteroposterior (AP) and ML COM displacement in order to maintain their balance.[16] They also show altered AP and ML movement of the head trunk while walking,[17–19] these changes also appear during stair ascent and gait initiation.[20,21]

Obstacle crossing is a challenge for individuals with PD. To successfully cross an obstacle, individuals should have greater toe clearance, greater hip angles, greater COM displacement, faster COM velocity, and greater COM-COP separation distance than level-ground walking.[22–24] Healthy older adults performed differently from young people when crossing an obstacle with slower gait speed and shorter step length than their everyday walking.[25,26] Step length prior to crossing an obstacle, toe clearance, and COM-COP separation distance have been used to measures dynamic postural stability. A few studies have examined the PD population during obstacle crossing. PD individuals had changes in their COM-COP separation distance during obstacle crossing when compared to older adults.[27–29] Moreover, COM movements in the ML direction were increased and clearance height of the leading foot and trailing foot were increased by increasing the ML sway of their COM.[30–32] They maintain postural stability by increasing their single leg support time slowing the AP movement of their COM and increasing ML movement.[32] The understanding of the effects of PD on dynamic postural stability is limited. Furthermore, the study findings were based on participants with PD who showed big variations in the severity (mild-to-moderate to severe).[30,31] The reported findings are also based on relatively small sample size (n = 10 with PD).[32]

To improve management of this disease and quality of life, understanding the dynamic postural stability of this population is needed. The purpose of this study was to examine the gait and dynamic postural stability during obstacle crossing in the individuals with early-stage PD compared with that in older healthy adults (HOA). The obstacle was set to a fixed height of 20 centimeters. This obstacle height closely simulated daily obstacles such as stairs and curbs. It was hypothesized that compared to the HOA group, the PD group would show significant differences in the following measures: 1) decreased gait speed, crossing stride length, pre- and post-horizontal distance, toe and heel clearance distance; 2) decreased AP COM displacement and velocity, and increased ML COM-COP separation distance; and 3) decreased maximum joint angles and ROM of the hip, knee, and ankle. Moreover, SLS and timed up and go (TUG) test scores would be significantly different between the two groups. This study would help to advance the understanding of PD related changes in gait and postural stability and contribute to the development of intervention programs to improve the gait and postural stability.

Methods

Participants

Sixteen individuals diagnosed with idiopathic PD in H&Y stages 1 to 2, and sixteen age- and sex-matched HOA participated in this study (Table 4.1). Recruitment of the participants was conducted through: (1) referrals from local medical clinics (i.e., physician/neurologist offices); and (2) local support groups associated with *Parkinson's Canada*. The participants were included if they had no neuromuscular injuries in the last two years and were able to stand and walk unassisted. The participants were excluded if they showed impaired mobility, dementia, cardiovascular disease, poorly controlled hypertension, or if they were currently on medications known to impair balance. The participants' written consent was obtained prior to their participation. This study has been approved by the university's research ethics review board and conformed to the World Medical Association Declaration of Helsinki.

Table 4.1 Participants' demographics, mean (SD)

Characteristics	PD (n=16)	HOA (n=16)	*p*
Sex (Female/Male)	7/9	7/9	1.00
Age (year)	72.3 (6.8)	68.8 (7.1)	.166
Weight (kg)	70.0 (16.9)	71.3 (9.9)	.791
Height (cm)	171.3 (10.5)	169.1 (8.1)	.497
MoCA	26.0 (2.9)	24.9 (4.5)	.444
H&Y stage	1.3 (0.5)	NA	
UPDRS-III, ON-medication state	21.0 (8.5)	NA	
Disease Duration	7.0 (5.4)	NA	
Exercise:			
Minutes/session	50.9 (16.9)	53.4 (35.5)	.801
Days/week	3.9 (1.5)	4.3 (2.0)	.488

Note. Abbreviations: PD, Parkinson's disease; HOA, healthy older adults; MoCA, Montreal Cognitive Assessment; H&Y, Hoehn & Yahr; UPDRS-III, Unified Parkinson's Disease Rating Scale (motor-subsection); NA, not applicable.

Data Collection

Information about their health backgrounds, physical activity, and/or exercise levels were obtained through telephone communication. The participants' general cognitive function was assessed using the Montreal Cognitive Assessment (MoCA). The PD participants were tested in the ON-medication state, within 1 to 2.5 hours after their last medication dose. All test and data were performed and collected at the Human Movement Biomechanics Laboratory.

Obstacle Crossing Tests

Three-dimensional motion of obstacle crossing in the participants was captured using a ten-camera VICON system (Oxford Metrics, Oxford, UK) at 200 Hz. Ground reaction forces were recorded using four force plates at 2000 Hz (models 9286AA, Kistler Instruments Corporation, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA) embedded in the middle of the walkway. Thirty-nine reflective markers were attached to the skin or over the participants' clothing in accordance with the Plug-in-Gait marker set (Oxford Matrices), as modified from the Helen Hayes marker set. The participants were asked to cross a 20-cm high obstacle that was setup in the middle of an 8-meter walkway at their self-selected comfortable pace. They were allowed to cross the obstacle with their self-select limb as the leading limb and with their comfortable shoes. Five successful trials of obstacle crossing were collected; a trial was deemed successful if the participants do not make contact or trip on the obstacle.

Single Leg Stance and Timed-up-and-go

The SLS test required the participant to stand on either the left or right leg for as long as possible with their hands placed on their hips. A coin toss was used to determine the order of the stance leg. The test was performed three times with eyes open (EO) and three times with the eyes closed (EC); the best time of each condition was reported.[33,34] One trial of the TUG test was collected, this test measured the participant's time (in seconds) to stand up from a chair, walk 3 m (9.8 ft), turn around, walk back to the chair, and sit down, with a shorter time indicating better mobility.[35] The participants were asked to keep their shoes on while performing the two tests.

Table 4.2 Summary of the definitions for studied variables.

Variables	**Definition**
Gait variables	
Crossing stride length	The anterior-posterior (AP) displacement between the heel strike (initial contact) of the TF before the obstacle to heel strike of the TF after the obstacle.(Naghdlou, 2021)
Crossing step length	The AP displacement between the heel strike (HS, initial contact) of the TF before the obstacle to the HS of the leading foot (LF, or crossing limb) after the obstacle.(Li et al., 2018)
Crossing width	The medial-lateral (ML) displacement between HS (initial contact) of the TF before the obstacle to heel strike of the LF (crossing limb) after the obstacle.(Li et al., 2018)
Gait speed	The speed between HS (initial contact) of the LF before the obstacle to HS of the TF after the obstacle.
Crossing speed	The speed of the crossing stride.(Naghdlou, 2021)
Obstacle clearance variables	
Toe and heel clearance	The displacement between the toe and heel, respectively, of the LF to the top of the obstacle.
Pre-horizontal distance	The horizontal distance between toe marker on the TF and the obstacle prior to crossing.(Naghdlou, 2021)
Post-horizontal distance	The horizontal distance between heel marker on the LF and the obstacle after crossing.
Dynamic postural stability variables	
COM displacement at AP & ML	The change in position of the center of mass (COM) during one crossing stride.
COM velocity at AP & ML	The velocity of the COM during one crossing stride.
COM-COP separation at AP & ML	The displacement between COM and center of pressure (COP) during one crossing stride.

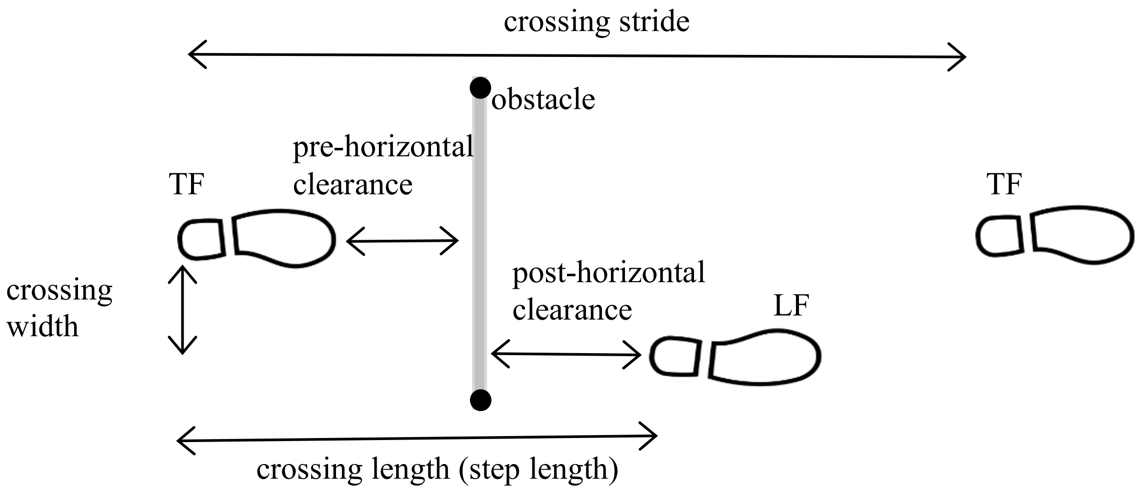

Figure 4.1. Illustration of the definitions of the gait parameters. Note: ● two markers were attached on top of the left and right corners of the obstacle. The position of the trailing foot (TF) and leading foot (LF) are shown during obstacle crossing.

Data processing and analysis

The studied variables and their definitions are summarized in Figure 4.1 and Table 4.2. The data processing approaches were reported in previous studies.[24,36] Briefly, the 3D joint angles of the lower limbs were obtained from Vicon Nexus (Oxford Metrics) and processed using the Plug-in-Gait model (Oxford Metrics). One gait cycle was defined from the instance of foot contact to the subsequent foot contact of the same foot. The temporospatial, kinematic, and kinetics parameters in terms of crossing speed, crossing stride length, toe and heel clearance height, COM displacement and velocity, COM-COP separation distance, the computed joint angles and joint moments of the hip, knee, and ankle along the frontal and sagittal planes were exported to MATLAB (MathWorks, Natick, USA) to average and calculate the maximum and minimal values of each trial of the movement. Joint angle and moment data were normalized to one gait cycle.

Differences in demographic variables between the two groups were tested using chi-square and independent-sample *t* tests depending on the variable's type after testing for normal distribution.

Independent-sample *t* tests were used to examine any difference in the measures between the two groups. A Bonferroni correction was not carried out due to the exploratory nature of the study and to avoid a type-I error. A $p \leq 0.05$ was considered statistically significant. All statistical operations were performed using SPSS software version 20 (SPSS Inc., Chicago, IL, USA). In order to better understand the changes in magnitude of the measures related to PD, the difference in percent for the studied variables was calculated between the PD and HOA groups.

Results

No significant differences between the PD and HOA groups were found in their demographic characteristics. Both groups' physical activity/exercise level, and MoCA scores were comparable. All participants successfully completed the obstacle crossing trials.

Single Leg Stance and Timed Up and Go tests

Compared to the HOA group, the PD group showed significantly shorter single-leg support time with (57.4 ± 41.7 s vs. 23.6 ± 20.9 s, $p = .009$) and EC (11.3 ± 8.8 s vs. 3.9 ± 2.5 s, $p = .004$). TUG time was similar between the PD and HOA groups (12.7 ± 3.2 s vs. 11.4 ± 2.0 s, $p = .189$), the difference was not significant.

Gait variables

No significant difference in gait variables was found between two groups (Table 4.3). There were no significant differences between the HOA and PD groups during obstacle crossing in terms of their gait speed and crossing speed, or stride length of their leading or trailing foot.

Obstacle clearance and dynamic postural stability variables

No significant differences were found in toe and heel clearance distance, and pre- and post-horizontal distance of the leading foot and trailing foot. The PD group had a smaller AP COM displacement and bigger ML COM displacement than the HOA group (Table 4.3), however these differences were not significant.

Table 4.3 Variables of gait, clearance, and postural stability in Parkinson's disease (PD) and healthy older adult (HOA) groups, mean (SD)

	PD (*n* = 16)	HOA (*n* = 16)	*p*	% difference in mean values
Gait variables				
Gait speed (m/s)	0.97 (0.25)	1.09 (0.13)	.075	12.4
Crossing speed (m/s)	0.92 (0.24)	1.03 (0.14)	.105	4.5
Crossing stride length of LF (m)	1.35 (0.26)	1.41 (0.17)	.282	6.9
Crossing step length (cm)	60.9 (16.1)	66.4 (9.7)	.142	8.6
Crossing width (cm)	6.7 (4.0)	8.1 (4.6)	.365	18.6
Obstacle clearance variables				
Toe clearance distance of LF (cm)	20.7 (5.4)	19.8 (6.0)	.627	11.4
Heel clearance distance of LF (cm)	19.4 (6.6)	17.8 (7.4)	.495	8.1
Pre-horizontal distance of TF (cm)	25.1 (7.1)	26.6 (9.5)	.641	16.5
Post-horizontal distance of LF (cm)	21.5 (9.5)	25.5 (13.6)	.171	13.4
Dynamic postural stability variables				
Max AP COM displacement (cm)	138.2 (25.5)	149.9 (14.9)	.223	8.1
Max ML COM displacement (cm)	9.3 (4.1)	7.9 (3.0)	.125	16.5
Max AP COM velocity (cm/s)	116.2 (30.8)	132.9 (16.4)	.080	13.4
Max ML COM velocity (cm/s)	22.0 (6.2)	19.9 (6.7)	.160	10.0
Max AP COM-COP separation (cm)	35.0 (11.6)	36.1 (8.6)	.674	3.1
Max ML COM-COP separation (cm)	9.5 (4.1)	8.7 (3.9)	.119	9.1

Note. Abbreviations: AP: anterior-posterior, COM: center of mass, COP: center of pressure, LF: leading foot, max: maximum, min: minimum, ML: medial-lateral, TF: trailing foot. *$p < .05$ vs. HOA, **$p < .001$ vs. HOA.

Joint angles and range of motion of the lower limb

Joint angles and ROM of the lower limb for leading and trailing limbs during obstacle crossing are reported in Table 4.4 (*below*). Significant differences in hip and knee angles and knee ROM were found during obstacle crossing between the two groups. Changes in flexion-extension and abduction-adduction angles of the hip are illustrated in Figure 4.2 (*below*). At the hip, adduction angle of the leading limb was significantly larger between the PD group compared to the HOA group (p = .037). Hip flexion angle of the trailing limb was significantly smaller between the PD group compared to the HOA group (p = .024). At the knee joint, adduction-abduction ROM was significantly larger for the PD group than the HOA group (p = .012). No significant group differences were found for the ankle angles and ROM at the ankle joints.

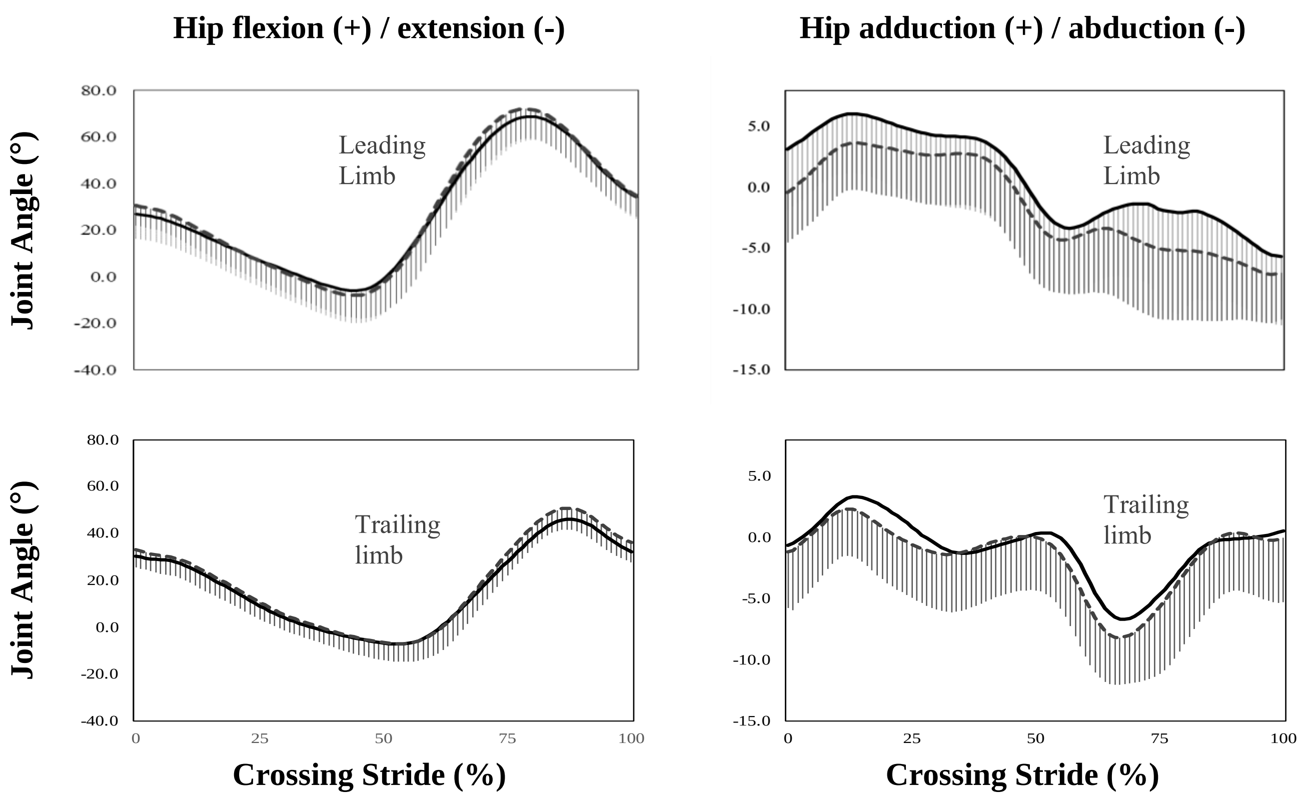

Figure 4.2. Angular displacement of the hip flexion-extension (left) and abduction-adduction (right) of the leading (top) and trailing (bottom) during obstacle crossing. The angle data has been time normalized to one crossing stride from heel strike (initial contact) before the obstacle to heel strike (HS) after the obstacle. The joint angles of the Parkinson's disease (PD) group are represented by the solid line (—) while the healthy older adult (HOA) group is represented by the dashed line (---).

Table 4.4 Maximum joint angles and range of motion (ROM) in Parkinson's disease (PD) and healthy older adult (HOA) groups during obstacle crossing, mean (SD)

	PD (*n* = 16)	HOA (*n* = 16)	*p*
Hip joint			
Flexion angle of LL (°)	70.0 (9.9)	73.5 (12.0)	.253
Flexion angle of TL (°)	47.5 (8.5)	51.7 (8.9)	**.024***
Adduction angle of LL (°)	7.4 (4.6)	4.7 (4.1)	**.037***
Adduction angle of TL (°)	5.3 (5.7)	3.8 (4.0)	.177
Flexion-extension ROM of LL (°)	77.1 (11.4)	82.8 (9.7)	.266
Flexion-extension ROM of TL (°)	55.3 (9.4)	59.7 (6.9)	.176
Adduction-abduction ROM of LL (°)	15.4 (5.2)	13.9 (2.9)	.145
Adduction-abduction ROM of TL (°)	13.9 (4.2)	12.8 (3.0)	.328
Knee joint			
Flexion angle of LL (°)	105.0 (33.3)	112.2 (11.1)	.378
Flexion angle of TL (°)	113.6 (17.3)	119.8 (13.4)	.271
Adduction angle of LL (°)	40.4 (25.4)	49.1 (14.2)	.734
Adduction angle of TL (°)	38.8 (22.4)	28.9 (18.4)	**.028***
Flexion-extension ROM of LL (°)	101.6 (25.6)	110.9 (12.5)	.273
Flexion-extension ROM of TL (°)	113.3 (22.1)	117.3 (14.6)	.602
Adduction-abduction ROM of LL (°)	43.5 (20.3)	47.3 (10.3)	.529
Adduction-abduction ROM of TL (°)	43.9 (17.7)	31.9 (15.3)	**.004***
Ankle joint			
Flexion angle of LL (°)	21.1 (6.5)	18.6 (5.3)	.316
Flexion angle of TL (°)	22.1 (10.5)	20.7 (5.5)	.616
Adduction angle of LL (°)	6.3 (7.4)	5.1 (2.6)	.217
Adduction angle of TL (°)	7.1 (5.0)	6.1 (4.2)	.292
Flexion-extension ROM of LL (°)	38.7 (14.3)	33.0 (11.9)	.284
Flexion-extension ROM of TL (°)	32.4 (8.9)	32.9 (10.9	.624
Adduction-abduction ROM of LL (°)	8.7 (6.7)	8.6 (6.3)	.899
Adduction-abduction ROM of TL (°)	11.9 (9.3)	10.6 (4.9)	.668

Note. Abbreviations: AP: anterior-posterior, COM: center of mass, COP: center of pressure, LL: leading limb, max: maximum, min: minimum, ML: medial-lateral, TL: trailing limb. *$p < .05$ vs. HOA, **$p < .001$ vs. HOA.

Discussion

This study examined the gait and dynamic postural stability during obstacle crossing of the early-stage PD individuals and compared the measures with their healthy counterparts. Results showed there were significant differences in the SLS tests with EO and EC between the two groups. Biomechanical analysis of obstacle crossing found that, compared to the HOA group, the

PD group presented no significant differences in the measures such as gait and crossing stride length, crossing width, clearance distance of the heel and toe, or foot placement to the obstacle before and after crossing. The displacement and velocity of the COM and separation of the COM-COP in the ML direction were not different between the two groups. The PD group showed significant differences in their angles and ROM of their hip and knee joints compared to the HOA group during obstacle crossing. Additionally, the large mean differences (over 10%) for gait speed, crossing width, toe clearance distance of the leading foot, pre- horizontal distance of trailing foot, post-horizontal distance of the leading foot, and maximal ML COM displacement were found between the PD and HOA groups. The findings suggest that individuals in the early-stage PD were able to cross the 20-cm high obstacle with altered gait and postural stability.

The significantly shorter SLS with EO and EC times from this study suggest the declined balance capacity in the early-stage PD individuals. The findings are comparable to two published studies.[10,37] Similar to Chomiak and colleagues' study,[10] the current study recorded the best time of three SLS trials but without a pre-set time limit to perform this test. To our knowledge, this study was the first study to examine SLS with EC in PD participants. The PD group in this study had significantly shorter SLS with EC than our HOA group, indicating that performing this test was a challenge. Research found that PD individuals had longer TUG test time than their age-matched healthy adults.[38–40] This study used same method as Morris and colleagues' study.[41] The PD group took a longer time to complete the TUG compared to the HOA group, but the difference was not significantly different. The TUG time of the PD participants from the published studies were shorter than the current study. This might be because their PD participants were younger and with more severe PD symptoms (H&Y 1 to 3).[42,43] In the current study, the HOA and PD participants were instructed to perform the TUG test at their self-selected, comfortable walking speed. The discrepancy between our findings with the past studies could be due methodological differences but may reflect closer to their everyday walking performance abilities.

Gait speed and crossing step length were reduced in the PD compared to the HOA group that further support the findings from the published studies. In these studies, obstacles were set at 10% of body height,[32] 10% of leg length,[29] and half of knee height, respectively.[44] Gait speed, step length and stride length were significantly reduced. In the current study, gait speed and crossing step length were reduced in the PD group but did not show significant differences compared to the HOA group. The reasons might be that the PD participants in this study were in the earlier stages of PD and on their PD-medication as well as, had lower motor symptoms (i.e., UPDRS-III scores) than the PD participants in the published studies.[32,44] The findings could imply that the current study's PD participants were active, and in good-shape and health, their walking performance and ability to cross over an obstacle were not severely impeded. The spatial measures during obstacle crossing were therefore not significantly different between the PD and HOA groups.

Toe and heel clearance distance were smaller for the PD group than the HOA group, the difference was not significant. The findings are consistent with the previous studies in which the obstacle heights were different from ours.[29,30,32,45] In the current study no significant difference was found in the pre- and post-horizontal distance of the leading or trailing foot. Stegemöller and colleagues reported that when crossing over an obstacle set to 10% body height, the post-horizontal distance of the trailing foot showed a significant difference between PD individuals and healthy control group.[32] The findings from this study do not support Stegemöller and colleagues' but were consistent with Liu and colleagues' study. The trailing foot of PD participants was place closer to the obstacle than the control group after crossing an obstacle at heights of 10%, 20%, and 30% of leg length, respectively, but no significant difference.[30] It appears that the PD group in the current study were able to adjust the clearance distance of their heel and toe according to the obstacle's height. The shorter post-horizontal distance presented by the PD group compared to the HOA group in the current study indicates that their gait has been altered. To ensure enough clearance height of the toe and heel, the PD group shortened their step length and stride length. This type of gait is thought to be a conservative strategy for maintaining dynamic stability.[46–48]

The AP COM velocity in the PD group was 13% slower than the HOA group. It indicates that the PD participants' COM motion was slower in the AP direction than the HOA group. ML stability is worse in people with PD than older adults, especially during demanding conditions such as obstacle crossing that challenge their postural stability.[14,49,50] This cautious approach allows dynamic stability to be maintained at the cost of the speed in which the task is performed. Moreover, big variations in the motion of the COM are noted in the AP direction but was not significant; the SD of the COM velocity were 30.8 and 16.4 m/s for the PD and HOA groups, respectively. The AP COM displacement was 8% smaller in the PD compared to the HOA group, whereas ML COM displacement was 17% greater. The findings are consistent with published studies. Stegemöller and colleagues reported that the AP COM displacement was significantly smaller for the PD compared to the control group when crossing an obstacle at 10% of body height.[32] The ML COM displacement in their PD was 36% greater than their control group.[32] Galna and colleagues' study also supports Stegemöller and colleagues's study.[31] The current study's findings suggest that the PD group showed changes in postural stability in the ML direction.

No significant difference in the separation of the COM-COP distance in the AP/ML directions during obstacle crossing between the two groups. Additionally, the PD group had 3% smaller separation in the distance between COM-COP in the AP direction than the HOA group. Research has found that individuals with impaired postural control had *less* separation of their resultant (combined AP and ML directional values) COM-COP separation distance than people with no known neurological problems.[51] However, the difference in the COM-COP separation distance at ML direction between two groups is 9%, the PD group was greater than the HOA group. A smaller range in the AP motion of the COM and maximum AP COM-COP separation distance are suggested to be due to the disease-specific changes, that the participants using a conservative or cautious gait to cross over the obstacle.[32,51] Furthermore, increase in the ML COM-COP separation distance could be from the combined effects of PD and aging.[52,53] The larger ML COM-COP separation between the PD and HOA group could be disease-specific related changes to postural stability. The PD participants would need to compensate for this postural instability by sacrificing ML control of their COM movement to ensure that their heel and toe can clear over the obstacle. Aging related changes in the muscles of the hip joint, particularly the tensor fasciae latae and erector spine can influence regulation of the backward and lateral movement of the trunk.[54] Weakness in the muscles in older PD individuals could affect the ability regulating movement of the trunk,[31] which increases the ML COM-COP separation distance.

Hip adduction angle of the leading limb was significantly larger in the PD group compared to the HOA group while crossing the obstacle. In the trailing limb, hip flexion angle of the PD group was smaller while knee adduction angle and adduction-abduction ROM was bigger than the HOA group. Obstacle crossing was a challenge because the muscles surrounding the hip joint are affected due to the strength related changes of PD.[55–60] Larger SD values in the knee adduction-abduction angles was found in the PD than in the HOA group, this could be compensation for changes in the hip's muscles. Magdalini and colleagues reported significant differences in the flexion angles of hip, knee and ankle joints of their PD patients compared to their healthy adult when crossing obstacles set to 0%, 10%, and 20% of leg length.[61] This suggest that older adults prefer to use hip strategy to ensure good foot clearance.[62–65] This would create higher demands on the hip flexor and extensor muscles. Although the PD participants in the current study were able to cross over the obstacle, this was with changes to their hip flexion and adduction angles. They relied on both ankle and hip strategies to maintain balance when that their balance is challenged.[12] In contrast, young healthy adults prioritize and rely on ankle strategy alone, and are able to make the necessary adjustments.[66] Individuals with PD often will select an ineffective (hip) strategy that result in a fall or injury.[1–3] Training or strengthen the muscle surrounding the hip joint would help to improve postural control, thereby individuals with PD would be able to adequately respond with the necessary postural adjustments when their balance or posture is challenged.

One limitation of this study was that participants were allowed cross the obstacle with their self-selected leading limb. This would not have accounted for leg dominance. In this study, data from both the leading and trailing limbs were analyzed separately. Past studies asked their participants to cross only with their dominant limb, this specification could affect the interpretation of the data. The HOA group showed signs of mild cognitive impairment based on their MoCA scores, which may have affected their ability to adhere to the testing protocols and instructions.

This study examined the gait and dynamic postural stability of individuals in the early-stage of PD and compared to the measures from HOA during obstacle crossing. The individuals with early-stage PD crossed obstacle slowly with increased hip abduction and knee adduction of the trailing limb. Moreover, ML postural sway was increased, indicating changed dynamic postural stability. These findings suggest that individuals with early-stage PD could cross a 20-cm obstacle that is common in their daily living environment, but with altered movement and postural stability. Therefore, individuals with early-stage PD should be more cautious during their daily activities so as to prevent the risk of an injury or fall.

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Research article 4

Effects of an online 12-week Tai Chi intervention on gait and postural stability in individuals with Parkinson's disease

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Abbreviations

AP: Anterior-Posterior

COM: Center of Mass

COP: Center of Pressure

EO: Eyes Opened

EC: Eyes Closed

H&Y: Hoehn and Yahr

ML: Medial-Lateral

MoCA: Montreal Cognitive Assessment

PD: Parkinson's disease

SLS: Single Leg Stance

TC: Tai Chi

TUG: Timed-Up-and-Go

UPDRS-III: Unified Parkinson's disease Rating Scale – motor section

Abstract

Parkinson's disease (PD) affects gait and postural stability. Tai Chi (TC) is recommended for PD for management of the condition, however biomechanical understanding to its effects on gait and postural stability is limited. This study aimed to examine the effects of an online 12-week biomechanical-based TC intervention on gait and posture in people with PD. Fifteen individuals in early-stage PD were recruited (Hoehn & Yahr stages 1 to 2). The TC intervention program was 60 min session, three times weekly for 12 weeks. The pre- and post-intervention test in obstacle crossing, timed-up-and-go (TUG) test, and single leg standing (SLS) with eyes open (EO) and closed (EC) were conducted. Gait speed, crossing stride length, clearance height of the heel and toe, anterior-posterior (AP) and medial-lateral (ML) displacement and velocity of the center of mass (COM) and separation of the COM-center of pressure (COP) were analyzed. The participants significantly improved their pre- vs. post-TC intervention performance on TUG test ($p = 0.002$). During obstacle crossing, the participants significantly increased crossing stride length of the trailing foot, increased AP COM displacement and decreased ML COM-COP separation ($p < 0.05$); the maximal dorsiflexion angle of the leading limb significantly increased and maximal plantarflexion angle of the trailing limb significantly decreased ($p < 0.05$). A 12-week biomechanical-based online TC training was effective towards improvement of gait and postural stability among people in the early-stage of PD. The TC program and online training could be applied for management of PD.

Keywords: center of mass, Tai Chi, center of pressure, kinematics, obstacle crossing, joint angles

Introduction

Postural instability and altered gait are problems reported by those with Parkinson's disease (PD).[1] Those with PD have difficulties with everyday tasks such as walking due to changes in step width and step length that can slow their gait.[2,3] Exercise has been used in conjunction with drug therapy (such as levodopa, carbidopa) as standard of care to manage the symptoms related to PD.

Tai Chi (TC) is a body-mind exercise that is recommended for management of PD.[4] Practicing TC regularly can help to improve the movement capacity of people with PD.[5,6] So far, it is unclear whether TC training could improve postural stability during a challenging locomotion task such as obstacle crossing. Furthermore, the information on how TC programs are formulated or how TC forms are selected in the reported studies is lacking. There are a variety of TC style and movement forms. The differences in the movement characteristics of exercise could results in different training effects on muscle strength and motion control. Moreover, application of the research's findings is important for the development future program for PD.

Obstacle crossing is a daily activity that is especially difficult for those with PD. It has been used to examine dynamic postural stability in the healthy and PD population by analyzing the displacement and velocity of center of mass (COM), and COM-center of pressure (COP) separation distance.[7] In order to understand the impacts of TC on gait and dynamic postural stability for people with PD, this study examined the effects of a online 12-week TC intervention program developed based on the biomechanics of the TC forms on gait and postural stability. It was hypothesized that after the 12-week TC intervention during obstacle crossing the PD participants will improve gait indicated by increased gait speed, step length, and toe and heel clearance distance during obstacle crossing, and improve dynamic postural stability indicated by altering COM velocity and displacement, and COM-COP separation distance as well as improve static postural stability indicated by better scores on the single leg stance test (SLS) with eyes opened (EO) and closed (EC). This study would advance the understanding of the effects of TC training on gait and posture in people with PD.

Methods

Participants

Seventeen participants aged 50 to 75 with early-stage idiopathic PD (Hoehn & Yahr (H&Y) 1 to 2, mean: 1.4 ± 0.6; disease duration: 7.1 ± 5.7) were recruited (age: 71.7 ± 6.6 years, weight: 67.8 ± 16.0 kg, height: 171.2 ± 10.5 cm, Montreal Cognitive Assessment (MoCA): 26.1 ± 2.9). The study began January 2021 and ended December 2021. The participants were recruited from referrals from local medical clinics (i.e., physician/neurologist offices) and local support groups that are associated with *Parkinson's Canada*. Prior to the TC intervention, they had regular exercise on average 52.4 ± 13.7 minutes/session, 4.1 ± 1.1 days weekly. The participants had no neuromuscular injuries in the last two years and were able to stand and walk unassisted. Exclusion criteria of the participants included impaired mobility, dementia, cardiovascular disease, poorly controlled hypertension, or if the participant were currently on medications known to impair balance. The participants were tested in the "ON" medication state approximately 1 to 2.5 hours after their last medication dose. This study was approved by the university's research ethics review board and conformed to the World Medical Association Declaration of Helsinki.

Tai Chi intervention program

A biomechanical-based TC intervention program that include seven Yang-style forms was developed based on the TC theory and movement analysis of TC.[8,9] The participants were enrolled into an online intervention that taught the TC program. The participants met online via ZOOM for 60 minutes, 3 times weekly for 12-weeks. The class was led by TC instructors with more than four years of TC teaching experience. Each session began with 5 to 10 minutes of warm-up, 40 minutes of core activities, and finished with 5-minute cooldown activities. The participants were instructed to attend a minimum 2 classes/week and encouraged to practice at home in the days between each class. They were asked to complete an activity log of their daily TC practice to monitor their progress. The TC instructor and TC expert were present at each session to monitor participants' progress and to make sure that movements were being performed correctly.

Data collection

The data was collected at the Human Movement Biomechanics Laboratory before and after the 12-week TC intervention. The physical activity and/or exercise levels and health backgrounds of the participants were obtained through telephone communication. Their general cognitive function was assessed using the MoCA.

Obstacle crossing test: Motion capture data collection for gait during obstacle crossing were conducted. The three-dimensional motion capture was performed using a ten-camera VICON system at 200 Hz. Thirty-nine reflective markers were attached to the skin or over the participants' clothing in accordance with the Plug-in-Gait marker set (Oxford Matrices), as modified from the Helen Hayes marker set.[10] Ground reaction forces were recorded using four force plates at 2000 Hz (models 9286AA, Kistler Instruments Corp, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA) that were embedded in the middle of the walkway. The participants crossed a 20-cm-high obstacle that was set up in the middle of an 8-meter walkway at their self-selected comfortable pace and with their self-select limb as the leading limb and with their comfortable shoes. Data from five successful trials of obstacle crossing were collected.

SLS and timed up and go (TUG) tests: For the SLS test, the participants were asked to stand on either the left or right leg for as long as possible with their hands placed on their hips. This test was performed three times with the EO and three times with the EC; the best time of each condition was recorded. A coin toss was used to determine the order of the stance leg. The TUG test measured the participant's time (in seconds) to stand up from a chair, walk 3 m (9.8 ft), turn around, walk back to the chair, and sit down, with a shorter time indicating better mobility.[11] The participants performed both tests with their shoes on.

Data processing and analysis

The studied variables and their definitions are listed in Table 5.1.[12,13] To obtain the above-mentioned variables, the captured motion data was reconstructed and labelled in VICON Nexus software 2.8.0 (Oxford, UK). The crossing motion of both the left and right limbs were analyzed. The force plates data were filtered using a 4^{th} order Butterworth filter with a cut-off frequency of 6Hz. A three-dimensional reconstructed model of the participant was created using the Plug-in-Gait model. VICON Nexus and MATLAB software were used to analyze the data. Paired-sample *t* tests were used to compare the difference between the pre- and post-intervention effect for all studied variables. A *p* value of less than 0.05 was considered statistically significant. All statistical operations were performed using SPSS software (version 20).

Results

Fifteen participants completed the intervention (15/17, 88% completion), one participant discontinued due to (unrelated) back pain before starting. All participants completed the five trials of obstacle crossing successfully. One participant could not complete the SLS with EC test for the pre- and post-intervention sessions, their data was omitted.

Table 5.1. Summary of the definitions for studied variables.

Variables	Definition
Gait variables	
Crossing stride length	The anterior-posterior (AP) displacement between the heel strike (initial contact) of the TF before the obstacle to heel strike of the TF after the obstacle.[12]
Crossing step length	The AP displacement between the heel strike (HS, initial contact) of the TF before the obstacle to the HS of the leading foot (LF, or crossing limb) after the obstacle.[13]
Crossing width	The medial-lateral (ML) displacement between HS (initial contact) of the TF before the obstacle to heel strike of the LF (crossing limb) after the obstacle.[13]
Gait speed	The speed between HS (initial contact) of the LF before the obstacle to HS of the TF after the obstacle.
Crossing speed	The speed of the crossing stride.[12]
Obstacle clearance variables	
Toe and heel clearance	The displacement between the toe and heel, respectively, of the LF to the top of the obstacle.
Pre-horizontal distance	The horizontal distance between toe marker on the TF and the obstacle prior to crossing.[12]
Post-horizontal distance	The horizontal distance between heel marker on the LF and the obstacle after crossing.
Dynamic postural stability variables	
COM displacement at AP & ML	The change in position of the center of mass (COM) during one crossing stride.
COM velocity at AP & ML	The velocity of the COM during one crossing stride.
COM-COP separation at AP & ML	The displacement between COM and center of pressure (COP) during one crossing stride.

Unified Parkinson disease scale (motor section), SLS and TUG tests

Among the PD participants who completed the TC training, the Unified Parkinson's disease Rating Scale – motor section (UPDRS-III), pre- and post-intervention changes in their SLS with EO (24 vs. 16 s, respectively) and EC (3.4 vs. 8.4 s, respectively) times. The mean TUG time of the participants was significantly faster by 1.6 s (95% confidence interval (CI), 0.7 to 2.6; $p < 0.02$).

Variables of gait, obstacle clearance, and joint angles

The mean and SD of the gait measures during obstacle crossing from pre- and post-intervention tests (Table 5.2 *below*). The mean stride length significantly increased 3.6 cm in the trailing foot (95% CI, -7.2 to 0.3; p = 0.036). Toe and heel clearance, and pre- and post-horizontal distance did not show significantly change. Ankle dorsiflexion angle of the leading limb increased 3.7 º (95% CI, -8.98 to -.65; p = 0.03) and plantarflexion angle of the trailing foot decreased 6.8 º (95% CI, -8.31 to 1.98; p = 0.02) significantly in the post-intervention tests (Table 5.3).

Table 5.2. Mean and SD of the clinical tests, gait, foot clearance, COM, and COP related variables from pre- and post- intervention tests.

Assessment	**Pre-intervention**	**Post-intervention**	**Change**	***P*-value**
Clinical				
UPDRS-III	21.1 ± 7.0	16.5 ± 8.9	-5.0 ± 7.8	.107
Timed Up-and-Go	12.7 ± 3.3	11.0 ± 3.3	-1.6 ± 1.7	**.002****
Single leg standing with eyes open	24.1 ± 21.3	33.3 ± 40.1	9.3 ± 31.3	.270
Single leg standing with eyes closed	3.4 ± 2.5	8.4 ± 15.2	5.0 ± 14.9	.214
Gait variables				
Gait speed (m/s)	0.96 ± 0.26	0.99 ± 0.24	0.03 ± 0.1	.086
Crossing speed (m/s)	0.93 ± 0.31	0.94 ± 0.22	0.01 ± 0.25	.797
Crossing stride length of LF (m)	1.34 ± 0.26	1.36 ± 0.28	0.01 ± 0.14	.292
Crossing stride length of TF (m)	1.38 ± 0.25	1.41 ± 0.23	0.04 ± 0.10	**.036***
Crossing step length (cm)	60.7 ± 16.4	61.6 ± 15.5	0.9 ± 8.9	.358
Crossing step width (cm)	6.5 ± 4.4	7.3 ± 4.3	0.8 ± 5.5	.263
Toe clearance distance of LF (cm)	20.8 ± 5.7	20.0 ± 5.1	-0.8 ± 3.5	.226
Heel clearance distance of LF (cm)	19.5 ± 6.8	18.3 ± 6.2	-1.1 ± 5.1	.286
Pre-horizontal distance of TF (cm)	25.4 ± 7.4	27.8 ± 7.0	2.8 ± 9.1	.186
Post-horizontal distance of LF (cm)	21.8 ± 9.3	21.7 ± 9.6	-0.1 ± 9.7	.928
COM, COP related variables				
Max AP COM displacement (cm)	139.2 ± 25.8	143.8 ± 22.6	3.0 ± 10.0	**.03***
Max ML COM displacement (cm)	8.8 ± 4.2	9.0 ± 4.6	0.4 ± 4.8	.503
Max AP COM velocity (cm/s)	116.0 ± 29.4	121.1 ± 23.2	3.4 ± 15.1	.111
Max ML COM velocity (cm/s)	21.1 ± 6.5	20.5 ± 7.6	-0.1 ± 10.1	.849
Max AP COM-COP separation (cm)	35.4 ± 11.3	33.7 ± 10.9	-3.7 ± 10.2	.838
Max ML COM-COP separation (cm)	9.7 ± 5.0	7.6 ± 3.4	-1.6 ± 6.6	**.03***

AP: anterior-posterior, COM: center of mass, COP: center of pressure, LF: leading foot, max: maximum, min: minimum, ML: medial-lateral, PA: physical activity, SD: standard deviation, TC: tai chi, TF: trailing foot. *p < .05 & **p < .001.

Dynamic postural stability variables

The mean of the max anterior-posterior (AP) COM displacement significantly increased by 3 cm (95% CI, -6.2 to -0.4; $p = 0.03$); also, the mean of the max medial-lateral (ML) COM-COP separation distance significantly decreased by 1.6 cm (95% CI, 0.2 to 3.6; $p = 0.03$).

Discussion

This study showed that an online 12-week biomechanical-based TC intervention is effective toward improvement of some aspect of gait and postural stability during obstacle crossing in people with early-stage PD. Significant improvements were reported on the TUG test. The PD participants' gait significantly improved which was indicated by an increase in the crossing stride length of their trailing foot. Their dynamic postural stability improved as indicated by increased maximal AP COM displacement and decreased maximal ML COM-COP separation distance.

The PD participants completed the TUG test significantly faster ($p = 0.002$). A past study reported a 1.9 s reduction on the TUG test in PD participants after 3 months of TC training ($p < 0.001$),[6] this finding is consistent with other TC intervention studies.[5,14] The findings suggest 2 to 6 months of TC training can help to improve movement and mobility. The current study's results for the UPDRS-III assessment were not significant. Whereas three published TC studies showed 3.3 to 6.3 points reduction in their participants' mean UPDRS-III scores after 12 and 24 weeks of training with significance.[5,6] The inconsistency with this study and published work could be related to the training intensity, in terms of training frequency and duration. The participants improved SLS test scores despite SLS being a challenge to perform with the EC for this population. To perform this, core muscles such as the internal oblique and the dominant side multifidus and proximal medial gastrocnemius muscles are activated to maintain stability.[15] The improvement of the SLS were however not significant.

The PD participants significantly increased crossing stride length of the trailing foot ($p < 0.05$). This finding was similarly reported in the older adults who regularly practiced TC.[16] Researchers report that people with PD reduced their stride length during obstacle crossing.[17] Furthermore, weakness in their dorsiflexor muscles could potentially lead to a trip on the obstacle or a fall.[18] Stride length increased after TC training; this would suggest that strength in the dorsiflexor muscles have improved. The participants increased their pre-horizontal distance from the obstacle and decreased slightly their heel clearance but maintained the same toe clearance height. From the reported findings, the participants appear to be less cautious as they did not need to position the foot closer to the obstacle before crossing.[19] Those who practice TC regularly crossed a 15-cm and 23-cm high obstacle with significantly faster and longer step length and significant higher toe clearance than the age- and exercise volume-matched older adults,[20] suggest that they have better movement and postural control capacities. When the obstacle is 20-cm higher, older adults who regularly practice TC crossed with lower heel and toe clearance heights.[21] This finding was consistent with the current study. The PD participants achieved a lower clearance height compared to the measures of before TC training.

The PD participants' dorsiflexion angle significantly increased 3.7 º in their leading limb and plantarflexion angle significantly decreased 6.8 ° in the trailing limb ($p < 0.05$) (Table 5.3 *below*). In Figure 5.1 (*below*), the joint angle curve for the ankle was smoother post-intervention, the peaks were diminished, and the joint angle pattern in AP and ML directions were more like the data of healthy age- and sex-matched controls from a previous study.[17] The significant changes at the ankle joints in both limbs indicate an alteration in the participants' gait. Compared to the study findings from healthy older adults, the plantarflexion angles for the PD participants were larger after TC training (14.4 ° and 19.7 °, respectively).[17] The trailing limb's plantarflexion angles of the participants were smaller compared to the healthy participants' angle during obstacle crossing from the mentioned study (15.6 ° and 20.7 °, respectively).[17] The difference in plantarflexion angles could be related to their changed postural stability. People with PD had poor sideward weight shifting abilities of their COM while standing; their toe clearance is increased ("over-lifted") during obstacle crossing.[18] The participants appeared to use ankle strategy during obstacle crossing. TC training appears to have changed the hip and ankle joint angles as well as increase stride velocity and stride length.[22,23] Whereas older adults will adapt a "swing hip" flexion strategy to achieve a higher leading toe clearance, young adult and experienced TC practitioners rely on ankle strategy.[22] The low toe clearance height observed after TC training.

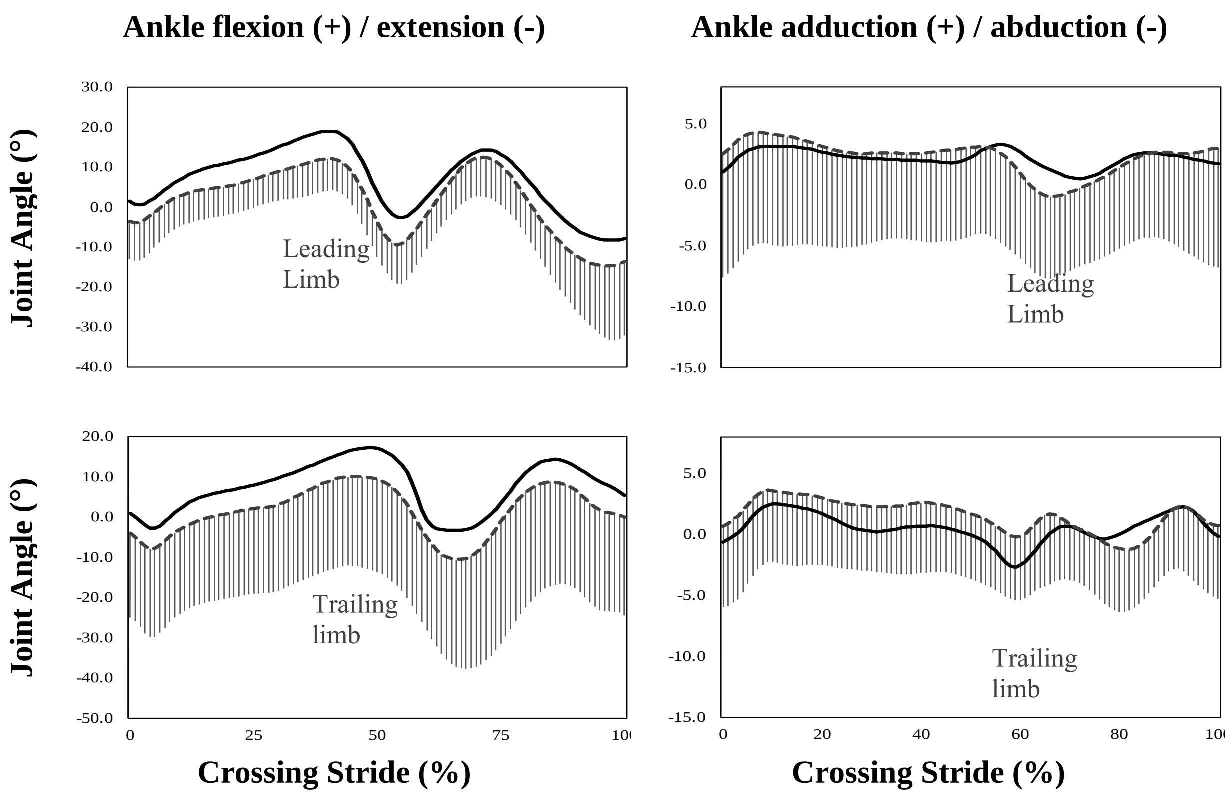

Figure 5.1. Angular displacement of the ankle flexion-extension (left) and abduction-adduction (right) of the leading (top) and trailing (bottom) limbs during obstacle crossing in pre (solid line) and post (dashed line) 12-week TC intervention. The angle data has been time normalized to one crossing stride from heel strike (initial contact) before the obstacle to heel strike (HS) after the obstacle.

Table 5.3. Mean and standard deviation (SD) of the joint angles and range of motion (ROM) of the lower limb of the participants with early-stage Parkinson's disease (n = 15) during obstacle crossing from pre- and post- intervention tests.

Joint	Session	Obstacle Crossing											
		Leading Limb						Trailing Limb					
		Angles				ROM		Angles				ROM	
		Flex (°)	Ext (°)	Add (°)	Abd (°)	Flex-Ext (°)	Add-Abd (°)	Flex (°)	Ext (°)	Add (°)	Abd (°)	Flex-Ext (°)	Add-Abd (°)
Hip	Pre-	68.9 ± 11.1	8.0 ± 12.3	7.1 ± 4.8	8.0 ± 6.7	76.9 ± 12.6	15.1 ± 5.0	46.1 ± 7.8	8.2 ± 13.0	5.4 ± 5.7	8.3 ± 5.1	55.0 ± 10.1	13.7 ± 3.9
	Post-	70.0 ± 9.4	6.0 ± 10.8	6.7 ± 4.4	8.5 ± 6.0	76.1 ± 13.5	15.2 ± 5.3	47.9 ± 8.2	6.7 ± 8.7	4.5 ± 5.6	9.0 ± 5.9	54.6 ± 10.9	13.5 ± 4.2
	p-Value	.996	.251	.549	.857	.299	.895	.745	.414	.857	.532	.515	.991
Knee	Pre-	94.7 ± 35.0	6.8 ± 40.9	35.4 ± 27.4	6.7 ± 16.4	101.5 ± 26.0	42.1 ± 20.6	111.2 ± 21.8	-0.3 ± 8.7	35.9 ± 23.5	7.3 ± 18.1	111.4 ± 26.1	42.6 ± 18.6
	Post-	107.3 ± 27.6	0.0 ± 8.6	49.6 ± 28.0	4.4 ± 15.5	107.3 ± 31.4	54.0 ± 21.9	106.0 ± 24.3	2.4 ± 5.9	40.3 ± 23.8	5.7 ± 17.6	108.4 ± 24.7	46.0 ± 19.1
	p-Value	.145	.471	.153	.412	.127	.287	.171	.103	.370	.338	.413	.614
Ankle	Pre-	21.8 ± 7.9	16.0 ± 11.6	5.8 ± 7.8	3.1 ± 6.8	37.8 ± 13.0	8.9 ± 7.4	22.4 ± 14.0	15.5 ± 16.5	6.2 ± 4.8	6.4 ± 11.4	37.9 ± 22.5	12.6 ± 11.4
	Post-	18.6 ± 7.5	19.7 ± 11.3	7.4 ± 8.9	2.9 ± 7.6	38.3 ± 12.3	10.3 ± 6.5	15.6 ± 22.7	17.8 ± 24.9	4.6 ± 21.5	6.9 ± 21.3	33.4 ± 9.7	11.5 ± 6.3
	p-Value	.272	**.026***	.655	.994	.210	.601	**.021***	.324	.361	.816	.586	.501

A "+" represents flexion or dorsiflexion; " – " represents extension and abduction. *$p < .05$, **$p < .001$.

The PD participants' ML COM-COP separation distance significantly decreased while AP COM displacement significantly increased. This suggest that dynamic postural stability has been altered. The COM-COP separation distance represents the interaction between the COM and COP.[7,24] Greater ML COM motion indicates poor dynamic control and reflect the individuals' sensation of instability during obstacle crossing.[24] A smaller ML COM-COP separation distance is thought to be a conservative strategy used during obstacle crossing. Older adults with postural instability exhibit greater and faster ML COM displacement than healthy older adults due to poor postural stability in the frontal plane.[7] PD patients demonstrate greater ML excursion of their COM during obstacle crossing compared to healthy controls.[25] They tend to keep their COM close to their COP during obstacle crossing and reduce the maximum AP COM-COP separation distance compared to healthy older adults.[19] The changes occurring after the online 12-week TC intervention could be related to an improved capacity of the PD participants to control their body's motion and posture.

Regular TC practice benefits muscle strength, postural control, and balance.[6,26,27] For the PD population, significant improvements were reported on the Berg Balance Scale after 12 weeks of TC training,[6,27] another study showed improvements in TUG performance after 24 weeks of TC training.[28] After 12 weeks of TC training, AP and ML COP displacement significantly increased during obstacle crossing as well.[29] This study's findings are consistent with the published work.[19,29] Both the AP COM displacement and AP COM velocity increased while AP COM-COP separation distance decreased. The increase in AP COM displacement indicated that trunk motion had increased, whereas AP COP displacement indicated that movement in the lower limbs was altered. This study did not show a significant change in ML COM displacement, but a significant decrease in ML COM-COP separation distance during obstacle crossing. Poor dynamic instability is linked to reduced ML postural control and a large ML COM-COP separation during obstacle crossing.[24,30] By maintaining a small ML COM-COP separation, this would be less demanding and therefore would be a safer option for people with PD as they step over the obstacle.

A limitation would be for the TUG test. For this test, the participants were asked to walk at their own "comfortable" speeds. Some variability could have been introduced between the laboratory sessions. Alternatively, if they were asked to walk as fast as possible, this may not truly reflect the actual changes in their walking speed; the participants were asked to "walk at their comfortable speed" to ensure that our data is comparable to other studies and to ensure that the guidelines on how to administer the TUG test were properly followed. The participants were allowed to engage in other forms of exercise such as boxing during the intervention period; this ensured that the participants enjoyed the intervention setup and that enough participants could be recruited for the study. There is limited research evidence on this topic, it is unknown whether the participants' engagement in other forms of exercises during the TC intervention could impact the measures. It is possible the effects of other forms of exercise and physical activity may play into the overall effectiveness of the intervention; therefore, the results of this study should be interpreted with some reservation.

Conclusion

The online 12-week TC intervention is effective towards improving postural stability and gait in individuals with early-stage PD. The TC training benefits to the improvement gait and postural stability, particularly dynamic postural stability by increasing their stride length of their trailing limb and increasing ankle dorsiflexion in their leading limb as well as improvement of their control in COM and COP motion in AP and ML direction during challenged locomotion, obstacle crossing. The online 12-week TC intervention program could be recommended to people with PD for improvement of their gait and postural stability.

Ethics approval statement

The study was approved by the human ethics committee of the University of Ottawa. The participant was a volunteer, without a monetary incentive and were informed about the use of their information. Informed consent from the participant was obtained.

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Research article 5

Effects of an online 12-week Tai Chi intervention on the electromyography activity of the lower limb muscles of individuals with Parkinson's disease during obstacle crossing

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Abstract

Objective**:** This study aims to examine the effect of an online 12-week Tai Chi (TC) intervention on the neuromuscular activity of the lower limb muscles of people with Parkinson's disease (PD) during obstacle crossing.

Design**:** Pre- and post-intervention comparisons were conducted within and between groups.

Setting**:** Experiment was conducted in the University of Ottawa's biomechanics laboratory.

Participants**:** Individuals with early-stage PD (n = 15, age 72.0 ± 6.9 years, Hoehn & Yahr 1 to 2) and age- and sex-matched healthy controls (HC) (n = 15, age 67.9 ± 6.4 years) were evaluated.

Main Outcome Measures**:** The main outcome measures were the ratio of the peak electromyography (EMG) activity and the integrated EMG (iEMG) activity and the ratio of the peak EMG and iEMG antagonistic pairs of the left and right lower limb muscles during obstacle crossing and walking. The muscles evaluated were rectus femoris (RF), adductor longus (ADDL), tibialis anterior (TA), semitendinosus (ST), gluteus medius (GMed), tensor fasciae latae (TFL), medial and lateral gastrocnemius (MG), and lateral gastrocnemius (LG). Joint angle and range of motion of the lower limb were also determined.

Results**:** In the pre-TC intervention test, the EMG activity was significantly different between participants with PD and HC. The PD group had significantly higher peak EMG ratios of ADDL, GMed, and TFL in the leading limb than the HC group ($p < 0.05$). After the 12-week TC intervention, the PD group showed significantly increased iEMG activity ratio of the TA in the leading and trailing limbs, decreased iEMG activity ratio in the TFL of the leading limb ($p < 0.05$) and decreased peak EMG ratio of the GMed and ADDL muscle pairs in the trailing limb ($p < 0.05$)

compared with the measures before the intervention. After the intervention, no significant differences in the iEMG of GMed and TFL were found between PD and HC groups; however, the peak EMG ratio of the ADDL in the leading and trailing limbs was significantly different between the two groups ($p < 0.05$). Moreover, the iEMG ratio of the GMed and ADDL muscle pairs of the leading limb significantly increased. The 12-week TC intervention significantly increased the dorsiflexion angles of the leading leg and decreased the plantaflexion angle of the trailing leg of participants with PD during obstacle crossing.

Conclusion**:** The biomechanical-based online 12-week TC program significantly improved the muscle activity of the GMed, TFL, and TA of participants with PD by changing the lower limb kinematics during obstacle crossing. The proposed intervention could be recommended to people with PD for management of the neuromuscular function of lower limb muscles.

Keywords: Tai Chi, neuromuscular, postural stability, joint angles, obstacle crossing, electromyography.

1. Introduction

Parkinson's disease (PD) is a neurological condition that affects an individual's movement. The common symptoms of PD include bradykinesia (slowness in movement), altered posture, and gait problems. Changes in movement and posture are related to the weakness and stiffness of the muscles of the trunk and lower extremities [1]–[3]. Better understanding of neuromuscular changes in patients with PD will help manage this condition.

Surface electromyography (EMG) is a non-invasive tool used to assess changes in the neuromuscular functions of muscles. Participants with early-stage PD [Hoehn and Yahr (H&Y) stages 1–2] exhibit weakness in their erector spinae muscles when voluntarily extending and flexing their trunk [4] as well as decreased total activation of the distal part of the tibialis anterior and oblique muscles when performing obstacle crossing [5]. As the disease progresses into early-to-middle stages (H&Y 2 to 3), delayed onset and higher activation peaks of EMG in the tibialis anterior muscles occur during walking [6]. In the later stages of PD (H&Y > 3), abnormal timing and lower peak activation of the tibialis anterior and gastrocnemius muscles are reported during walking [7], [8]. Recent evidence confirms that PD-related changes in muscle activity include lower number of muscle recruitment in the lower limbs [9], [10] and increased co-activation of antagonistic muscles while walking [11], [12]. The changes in the muscle activity of the trunk and lower limbs greatly impact the movement capacity of people with PD.

Regular exercise can help maintain the health and well-being of people with PD. Research through EMG analysis found that the onset time and activation duration of the tibialis anterior and medial gastrocnemius in the PD population were significant delayed during forward and backward surface perturbation tests following 3 weeks of high-volume (450 minutes/week) adapted tango training [13]. A 17-week physical therapy with rhythmic auditory intervention significantly reduced the muscle asymmetry in the left and right lateral gastrocnemius muscles of participants with PD (H&Y stages 1.5 to 3) during walking; however, no significant difference in muscle activation (i.e., root mean square and modulation index) was found between the baseline and 17-week test sessions [14]. Another study reported that underwater gait training restored the recruitment pattern of the tibialis anterior of individuals with early-stage PD (n = 10, H&Y < 2) toward normal level during walking [15]. These findings are promising but are inconsistent and lack a distinct focus toward improvements in neuromuscular function. Previous works reported that exercise training did not significantly change the EMG activity in participants with PD [16]–[18].

Tai Chi (TC) is a body-mind exercise recommended for PD [21]. Regular TC practice can help maintain the health and well-being of people with PD [15,16]; however, the effect of TC training on neuromuscular function remains unclear. Studies used different forms of TC training for people with PD, but information on the selection of a suitable TC form for intervention is lacking. Differences in the styles and forms of the selected TC could influence training outcomes, such as muscle strength and postural stability, because of the biomechanical characteristics of TC movements. Our research team developed a TC intervention program based on the biomechanical analysis of TC forms [19]–[21]. However, the effects of the biomechanical-based TC program on neuromuscular activity of the lower limb of people with PD are unknown. The present study aimed to examine the effects of 12-week TC intervention on people with early-stage PD and compared the results between participants with PD and age- and sex-matched healthy participants. The intervention was conducted online given the social activity restriction due to COVID-19. During obstacle training, the EMG activity of the lower limbs would show significant differences between PD and HC groups in the pre-intervention test. The proposed TC intervention could significantly improve the neuromuscular activity of participants with PD and the healthy older adult populations. The findings could improve our understanding of neuromuscular activity changes in lower limbs following TC training in individuals with PD and elucidate the mechanisms underlying the exercise effects on neuromuscular activity in the population.

2. Methods

2.1. Participants

Table 6.1. Demographics and clinical characteristics of the participants with Parkinson's disease (*n* = 15) and age- and sex-matched healthy controls (*n* = 15)

Characteristics	PD (*n* = 15)	HC (*n* = 15)	*P-value*
Sex (Female/Male)	7/8	6/9	.724
Age (year)	72.0 ± 6.9	67.9 ± 6.4	.106
Weight (kg)	68.6 ± 16.4	72.5 ± 9.0	.423
Height (cm)	171.1 ± 10.8	169.1 ± 8.1	.559
MoCA	26.1 ± 3.0	24.9 ± 4.5	.418
H&Y stage	1.2 ± 0.4	n/a	
Disease Duration	9.0 ± 6.3	n/a	
Exercise:			
Minutes/session	54.3 ± 10.3	57.0 ± 33.6	.771
Days/week	4.1 ± 1.1	4.6 ± 1.7	.379

NOTE: Abbreviations: MoCA, Montreal Cognitive Assessment; HC, healthy controls; H&Y, Hoehn & Yahr; PD, Parkinson's disease.

Participants were recruited or referred from local medical clinics (i.e., physician and/or neurologist offices) and local support groups associated with *Parkinson's Canada*. The study involved 17 individuals with idiopathic PD and 15 healthy age- and sex-matched healthy adults, which formed the PD and healthy control (HC) groups, respectively (Table 6.1). All the participants were in the early stage of PD (H&Y 1 to 2). The participants had no neuromuscular injuries in the last two years and were able to stand and walk unassisted. The exclusion criteria were as follows: impaired mobility, dementia, cardiovascular disease, poorly controlled hypertension, and intake of medications to impair balance. Participants with PD were tested in the “ON” medication state approximately 1 to 2.5 hours after their last medication dose. This study has been approved by the university’s research ethics review board and conformed to the World Medical Association Declaration of Helsinki.

2.2. TC intervention

A biomechanical-based TC training program was developed based on analysis of kinematics, kinetics, and EMG activity of the lower limb of seven selected TC movements performed by an experienced TC master [19]–[21]. Participants with PD were enrolled in an online intervention seven-form TC program (Yang-style) [21]. The participants met online via ZOOM for 60 minutes, three times weekly for 12 weeks. The class was led by a TC instructor with the help of a TC expert with more than 4 years of teaching experience. Each session began with 5 to 10 minutes of warm-up, followed by 40 minutes of core activities, and finished with 5-minute cool-down activities. The participants were instructed to attend a minimum of two classes weekly and encouraged to practice at home in the days in-between each class. The participants were asked to complete an activity log of their daily TC practice to monitor their progress. The TC instructor was present at each session to monitor the participants’ progress and to make sure that movements were performed correctly.

2.3. Data Collection

Details of the data collection protocol and procedures were reported in the article titled *Effects of a biomechanical-based Tai Chi program on gait and posture in people with Parkinson’s disease: study protocol for a randomized controlled trial* [22]. Data were collected at the Human Movement

Biomechanics Laboratory. Participants with PD completed two sessions of data collection, namely, before and after the 12-week TC intervention. The participants in healthy control (HC) group had completed one session of data collection and served as baseline comparison data. The physical activity and/or exercise levels and health backgrounds of the participants were obtained through telephone communication. General cognitive function was assessed using the Montreal Cognitive Assessment (MoCA) tool.

2.4. Obstacle crossing test

Three-dimensional (3D) motion capture was performed using a 10-camera VICON system at 200 Hz. Thirty-nine reflective markers were attached to the skin or over the participants' clothing in accordance with the Plug-in-Gait marker set (Oxford Matrices), as modified from the Helen Hayes marker set [23]. Ground reaction forces were recorded using four force plates at 2000 Hz (models 9286AA, Kistler Instruments Corp, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA). These force plates were embedded in the middle of the walkway. The muscle activity of the left and right lower extremities was recorded using a 16-channel Trigno™ Wireless EMG System (SP-W01D, Delsys Inc., Boston, MA, USA). Wireless sensors were placed on the eight muscles on left and right lower limbs: rectus femoris (RF), adductor longus (ADDL), tibialis anterior (TA), semitendinosus (ST), gluteus medius (GMed), tensor fasciae latae (TFL), medial gastrocnemius (MG), and lateral gastrocnemius (LG). EMG sensor placement was performed in accordance with the SENIAM Project's guidelines [24]. The participants were asked to cross a 20 cm-high obstacle that was set up in the middle of an 8 m walkway at their self-selected comfortable pace and with their self-selected limb as the leading limb. They wore their comfortable shoes and performed five successful trials each of walking and obstacle crossing.

2.5. Data processing and analysis

Joint angle data: The 3D joint angles for the lower limbs were obtained using Vicon Nexus (Oxford Metrics) and the Plug-in-Gait model (Oxford Metrics). One gait cycle was identified from each trial for data analysis. A gait cycle was defined by one crossing stride of either the leading or trailing limb from the completion of foot contact before the obstacle to the subsequent foot contact after the obstacle for the same foot. The computed joint angles of the hip, knee, and ankle along the frontal and sagittal planes were exported to MATLAB (MathWorks, Natick, USA) to average and calculate the maximum and minimal values of each trial. The joint angle data were normalized to one gait cycle.

EMG data: The EMG data were processed using custom MATLAB (MathWorks, Natick, USA) script. The EMG signal was subjected to high-pass filter at 25 Hz with a 2^{nd} order dual-pass Butterworth filter, full-wave rectification, and low-pass filter at 10 Hz with 2^{nd} order dual-pass Butterworth filter with a 6 db/octave-filter slope. For each muscle, the ratio of the maximum or "peak" EMG amplitude (peak EMG) value and integrated EMG (iEMG) value were time-normalized to one crossing stride of the leading and trailing limbs obtained from the kinematic analysis. Moreover, amplitude-normalized to the peak values obtained from one crossing stride (i.e., peak EMG) to one walking gait cycle of each participant's averaged five walking trials were conducted. Peak normalization is necessary to compare the activity among muscles; the peak values of the averaged five walking trials were used because age and condition could affect their ability to reliably produce a maximum effort for normalizing reference [9], [25]. One crossing stride was defined from the instance of the foot strike before the obstacle to foot strike after the obstacle. Additionally, the peak EMG and iEMG ratios for the antagonistic muscle pairs called as "co-activation ratios" were calculated for comparison [26]–[28]. For the ratios, 1.0 indicates equal activation of the agonist and antagonist muscles, while greater than 1.0 indicates increased agonist activation compared with antagonist activation (vice versa) [27], [29]. The co-activation ratios represent the activation of the antagonistic muscle pairs that alter the stiffness of a joint to maintain postural stability [29]. Paired-sample *t* tests were used to evaluate differences in the outcome measures in the PD group between pre- and post-intervention tests and independent-sample *t* test to evaluate the differences in the outcome measures between PD and HC groups. A *p* value of less than 0.05 was considered statistically significant. To control for type I errors when performing multiple independent t-tests, Bonferroni correction was used for post-hoc analysis. All statistical operations were performed using SPSS software (version 20). All data are presented as mean and standard deviation (SD).

3. Results

Fifteen participants with PD completed the intervention (15/17, 88% completion), and one participant discontinued due to unrelated back pain before the start of the intervention. Figure 6.1 illustrates the peak EMG and iEMG ratios of each muscle during obstacle crossing and walking tests before and after the 12-week TC intervention. Table 6.2 lists the ratio of the peak EMG and iEMG of the leading and trailing limb muscles during obstacle crossing and walking before the 12-week TC intervention of participants with PD and age- and sex-matched HCs. Pre-intervention, participants with PD showed significantly higher peak EMG ratios of the adductor longus (11.7 vs. 4.3, 95% CI 1.7 to 13.1), gluteus medius (22.8 vs. 7.9, 95% CI .8 to 28.6), and tensor fasciae latae (32.6 vs. 10.2, 95% CI 2.7 to 41.5) ($p < 0.05$) in their leading limb than the HCs.

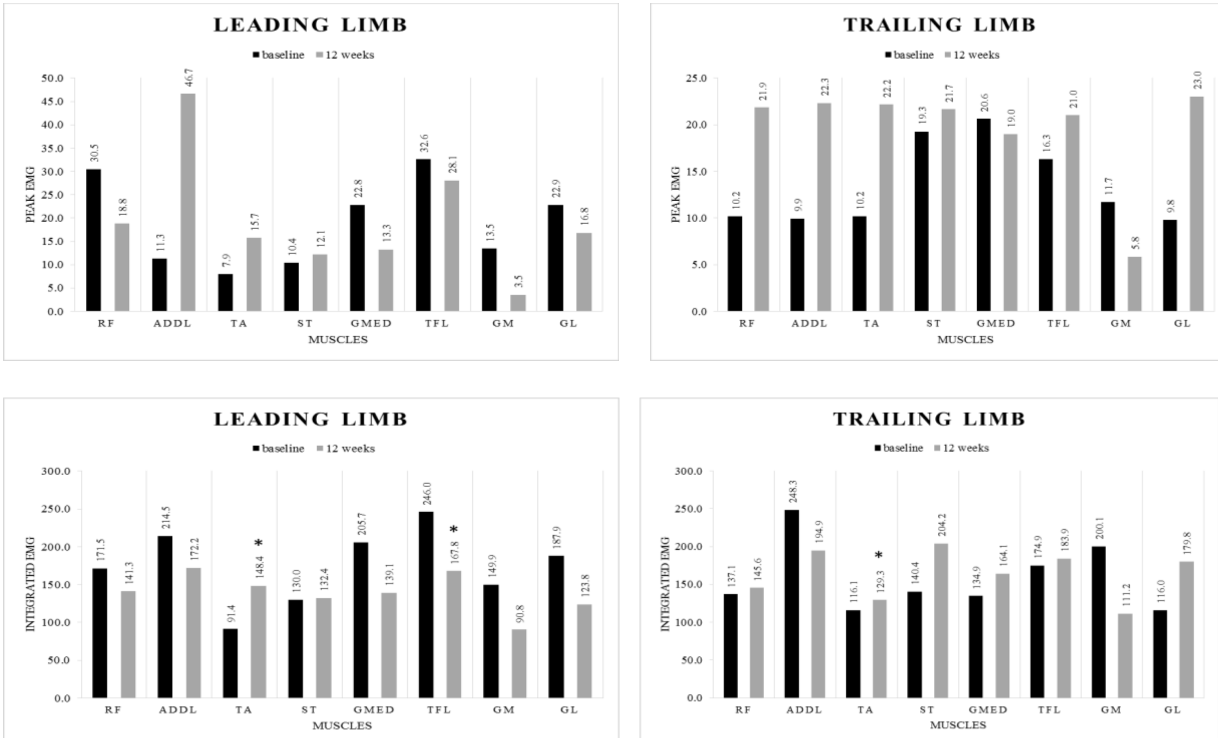

Figure 6.1. Illustration of the peak electromyography (EMG) (*top*) and integrated EMG (*bottom*) values presented ***as a ratio*** (i.e., no units) between the obstacle crossing and walking. The trials of the participants with Parkinson's disease (PD) (n = 15) were collected at baseline (*black*) and 12 weeks (*gray*) following the TC intervention. ADDL: Adductor Longus, GMed: Gluteus Medius, RF: Rectus Femoris, ST: Semitendinosus, TA: Tibialis Anterior, TFL: Tensor Fasciae Latae. * $p < 0.05$.

Figure 6.2 shows the raw and filtered EMG signals from the tensor fasciae latae muscle of the leading limb (*left*) and the tibialis anterior of the trailing limb in one participant. Table 6.3 lists the statistical analysis results of the ratio of the peak EMG and iEMG of the leading and trailing limb muscles during obstacle crossing and walking tests post-intervention. No significant differences in the peak EMG ratios of the gluteus medius and tensor fasciae latae of the leading limb were observed between participants with PD and HCs. For the adductor longus, the peak EMG ratio of participants with PD was significantly higher than that of HCs ($p < 0.05$). Moreover, the peak EMG ratio of the adductor longus of the trailing limb of participants with PD was larger (22.3 vs.

4.3, 95% CI 3.4 to 197.1), and the between-group difference was marginally significant (p = 0.054). The iEMG ratio of the of the adductor longus of the trailing limb decreased in participants with PD after the 12-week TC intervention; the difference between the participants with PD after the 12-week TC intervention was significant compared with that in HCs (194.9 vs. 152.7, 95% CI 3.4 to 197.1, respectively $p < 0.05$). Following the intervention, the iEMG value of the tibialis anterior in the leading and trailing limbs of participants with PD significantly increased by 62% (95% confidence interval [CI] -56.6 to 272.4, $p = 0.023$) and 11% (CI -106.1 to -1.92, $p = 0.044$), respectively; the iEMG value of the tensor fasciae latae decreased significantly in the leading limb by 32% (95% CI 36.0 to 275.4, $p = 0.015$). The peak EMG values was not statistically different.

Table 6.4 shows the ratio of the peak EMG and iEMG from antagonistic muscle pairs pre- and post-intervention in the PD group and the comparison of the measures between PD group and health control. After the 12-week TC intervention, the peak EMG ratio of the antagonistic muscle pairs for the gluteus medius and adductor longus of the trailing limb of participants with PD significantly decreased from 2.13 to 0.51 (95% CI 0.03 to 1.42, $p = 0.043$). Before the 12-week TC intervention, the iEMG of the antagonistic muscle pairs for the rectus femoris and semitendinosus in the trailing limb of participants with PD was lower and significantly smaller than that of HCs (0.84 and 0.98, respectively $p = 0.002$). After the 12-week TC intervention, the iEMG of the antagonistic muscle pairs for the gluteus medius and adductor longus in the trailing limb of participants with PD was lower and significantly smaller than that of HCs (0.78 and 1.29, respectively $p = 0.036$).

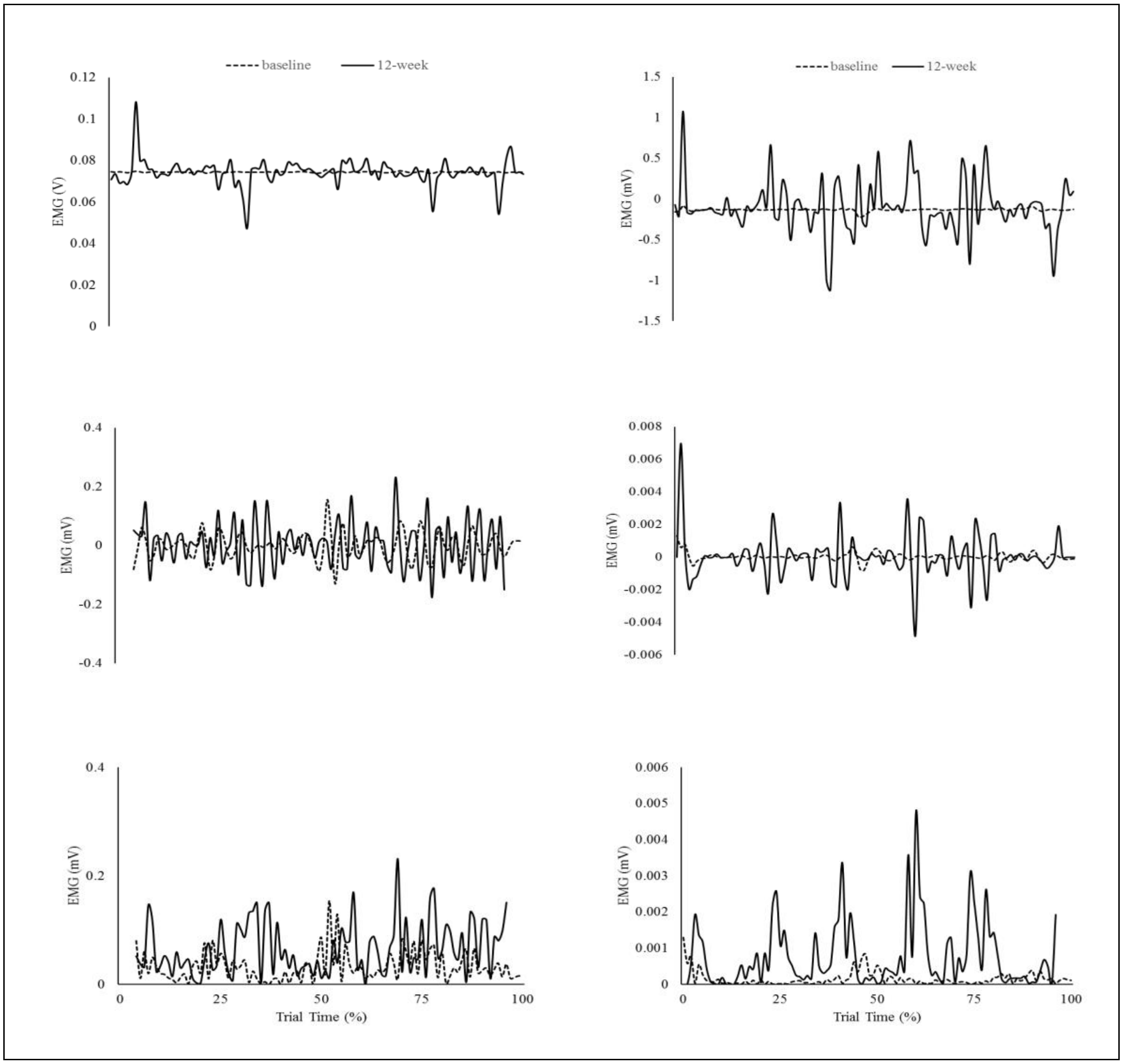

Figure 6.2. Raw electromyography (EMG) data (*top*) filtered EMG signal using a low-pass filtered at 10 Hz and a high-pass filtered at 25 Hz with 2nd order dual-pass Butterworth filter (*middle*), and full-wave rectified EMG signal (*bottom*). The tensor fasciae latae muscle of the leading limb (*left*) and tibialis anterior of the trailing limb (*right*) of one PD participant's obstacle crossing trial has been selected for illustration. The EMG signal was illustrated for the complete trial time (%) of one obstacle crossing trial.

Table 6.2. Ratio of the peak EMG and iEMG (mean and SD) of the leading and trailing limb muscles between obstacle crossing and walking before 12-week TC intervention in the Parkinson's disease (PD) participants (n = 15) and age- and sex-matched health controls (HC) (n = 15).

		Peak EMG							
Limb	Group	RF	ADDL	TA	ST	GMed	TFL	GM	GL
Leading	PD	33.9 ± 43.1	11.7 ± 9.9	8.8 ± 13.3	10.4 ± 11.9	22.8 ± 31.9	32.6 ± 41.1	13.5 ± 26.1	22.9 ± 36.7
	HC	9.1 ± 14.1	4.3 ± 4.2	3.2 ± 2.3	7.5 ± 8.9	7.9 ± 9.9	10.2 ± 13.3	2.7 ± 1.5	8.2 ± 14.4
	p-value[a]	.075	**.013***	.173	.567	**.040***	**.027***	.142	.100
Trailing	PD	10.2 ± 13.6	9.9 ± 14.7	10.2 ± 21.8	19.3 ± 31.3	20.6 ± 51.7	16.3 ± 28.6	11.7 ± 21.5	9.8 ± 21.9
	HC	7.6 ± 9.5	4.3 ± 3.4	3.2 ± 2.7	5.2 ± 6.1	6.3 ± 9.5	7.4 ± 7.1	5.2 ± 7.7	5.6 ± 7.6
	p-value[a]	.560	.182	.256	.151	.337	.327	.399	.526
		iEMG							
		RF	ADDL	TA	ST	GMed	TFL	GM	GL
Leading	PD	171.5 ± 201.2	214.5 ± 350.2	91.4 ± 86.6	130.0 ± 144.1	205.7 ± 243.6	246.0 ± 236.9	149.9 ± 152.0	187.9 ± 265.6
	HC	155.0 ± 88.3	112.3 ± 68.8	119.7 ± 39.7	168.8 ± 93.6	185.6 ± 242.5	303.0 ± 154.7	115.8 ± 24.0	185.4 ± 192.4
	p-value[a]	.476	.127	.886	.366	.378	.060	.088	.226
Trailing	PD	137.1 ± 138.7	248.3 ± 550.5	116.1 ± 146.2	140.4 ± 153.5	134.9 ± 123.2	174.9 ± 228.4	200.1 ± 298.3	116.0 ± 151.
	HC	173.7 ± 87.6	152.7 ± 72.6	125.4 ± 51.1	134.4 ± 41.9	156.2 ± 85.7	215.6 ± 129.6	139.2 ± 49.8	182.8 ± 100.0
	p-value[a]	.717	.389	.471	.865	.480	.515	.545	.737

[a] Between-group comparison PD (0w) vs. HC (0w) using independent sampled t-test. *p < .05, **p < .001.

Table 6.3. Ratio of the peak EMG and iEMG (mean and SD) of the leading and trailing limb muscles between obstacle crossing and walking after 12-week TC intervention in the Parkinson's disease (PD) participants (n = 15) and age- and sex-matched healthy controls (HC) (n = 15).

		RF	ADDL	TA	ST	GMed	TFL	GM	GL
Limb	Group	**Peak EMG**							
Leading	PD	21.0 ± 39.1	52.3 ± 90.7	15.7 ± 31.6	12.1 ± 32.2	13.3 ± 29.0	28.1 ± 57.6	3.5 ± 2.9	16.8 ± 47.6
	HC	9.1 ± 14.1	4.3 ± 4.2	3.2 ± 2.3	7.5 ± 8.9	7.9 ± 9.9	10.2 ± 13.3	2.7 ± 1.5	8.2 ± 14.4
	p-value[b]	.377	**.039***	.124	.419	.601	.245	.321	.319
	p-value[c]	.483	.139	.404	.352	.384	.958	.199	.875
Trailing	PD	21.9 ± 43.9	22.3 ± 42.3	22.2 ± 66.1	21.7 ± 48.0	19.0 ± 41.1	21.0 ± 47.0	5.8 ± 8.9	23.0 ± 50.7
	HC	7.6 ± 9.5	4.3 ± 3.4	3.2 ± 2.7	5.2 ± 6.1	6.3 ± 9.5	7.4 ± 7.1	5.2 ± 7.7	5.6 ± 7.6
	p-value[b]	.215	.054	.255	.186	.480	.291	.720	.160
	p-value[c]	.166	.084	.316	.196	.920	.297	.803	.155
		iEMG							
Leading	PD	141.3 ± 105.2	172.2 ± 191.3	148.4 ± 164.0	132.4 ± 132.4	139.1 ± 130.4	167.8 ± 200.1	90.8 ± 65.7	123.8 ± 143.6
	HC	155.0 ± 88.3	112.3 ± 68.8	119.7 ± 39.7	168.8 ± 93.6	185.6 ± 242.5	303.0 ± 154.7	115.8 ± 24.0	185.4 ± 192.4
	p-value[b]	.535	.108	.123	.364	.638	.608	.336	.457
	p-value[c]	.174	.914	**.023***	.522	.069	**.015***	.394	.702
Trailing	PD	145.6 ± 125.4	194.9 ± 197.7	129.3 ± 98.5	204.2 ± 171.9	164.1 ± 186.1	183.9 ± 156.8	111.2 ± 125.8	179.8 ± 209.8
	HC	173.7 ± 87.6	152.7 ± 72.6	125.4 ± 51.1	134.4 ± 41.9	156.2 ± 85.7	215.6 ± 129.6	139.2 ± 49.8	182.8 ± 100.0
	p-value[b]	.823	**.043***	.156	.293	.920	.817	.685	.479
	p-value[c]	.671	.945	**.044***	.266	.892	.862	.261	.307

[b] Between-group comparison PD (12w) vs. HC (0w) using independent sampled t-test, [c] Within-group comparison PD (0w) vs. PD (12w) using paired-sample t-test. *p < .05, **p < .001.

Table 6.4. Comparison of the ratio of antagonistic muscle pairs for peak EMG and iEMG values before and after TC-intervention in the PD group (n = 15) and the comparison of the measures between PD group and health control (HC) (n = 15).

		peak EMG of muscle pairs						iEMG of muscle pairs					
Group	Session	RF-ST		GM-TA		GMed-ADDL		RF-ST		GM-TA		GMed-ADDL	
PD	0w	LL: 3.24 (324%)	TL: 0.54 (54%)	LL: 1.64 (164%)	TL: 0.96 (96%)	LL: 1.95 (195%)	TL: 2.13 (213%)	LL: 2.12 (212%)	TL: 0.84 (84%)	LL: 1.63 (163%)	TL: 1.14 (114%)	LL: 0.94 (94%)	TL: 0.59 (59%)
	12w	LL: 1.05 (105%)	TL: 0.71 (71%)	LL: 0.19 (19%)	TL: 0.22 (22%)	LL: 0.17 (17%)	TL: 0.51 (51%)	LL: 1.00 (100%)	TL: 0.72 (72%)	LL: 0.68 (68%)	TL: 1.08 (108%)	LL: 0.56 (56%)	TL: 0.78 (78%)
	p-value[a]	.426	.522	.095	.304	.483	**.043***	.347	.072	.191	.287	.431	.169
HC	control	LL: 1.26 (126%)	TL: 1.39 (139%)	LL: 0.85 (85%)	TL: 0.29 (29%)	LL: 1.70 (170%)	TL: 2.13 (213%)	LL: 0.64 (64%)	TL: 0.98 (98%)	LL: 0.92 (92%)	TL: 1.10 (110%)	LL: 1.42 (142%)	TL: 1.29 (129%)
	p-value[b]	.394	.110	.662	.505	.950	.319	.815	**.002***	.284	.417	.557	.572
	p-value[c]	.216	.124	.147	.123	.576	.123	.816	.923	.234	.159	.479	**.036***

[a] pre- vs post- TC intervention test in PD participants using paired sample t-test, [b] PD participants pre- TC intervention test (0w) vs. HC participants,
[c] PD participants post- TC intervention test (12w) vs. HC (control).
*p < .05, **p < .001.

Table 6.5. Mean and standard deviation (SD) of the joint angles and range of motion (ROM) of the lower limb in the PD group during obstacle crossing from pre- and post-intervention tests.

Joint	Group	Obstacle Crossing											
		Leading Limb						Trailing Limb					
		Angles				ROM		Angles				ROM	
		Flex (°)	Ext (°)	Add (°)	Abd (°)	Flex-Ext (°)	Add-Abd (°)	Flex (°)	Ext (°)	Add (°)	Abd (°)	Flex-Ext (°)	Add-Abd (°)
Hip	Pre-	68.9 ± 11.1	8.0 ± 12.3	7.1 ± 4.8	8.0 ± 6.7	76.9 ± 12.6	15.1 ± 5.0	46.1 ± 7.8	8.2 ± 13.0	5.4 ± 5.7	8.3 ± 5.1	55.0 ± 10.1	13.7 ± 3.9
	Post-	70.0 ± 9.4	6.0 ± 10.8	6.7 ± 4.4	8.5 ± 6.0	76.1 ± 13.5	15.2 ± 5.3	47.9 ± 8.2	6.7 ± 8.7	4.5 ± 5.6	9.0 ± 5.9	54.6 ± 10.9	13.5 ± 4.2
	p-Value	.996	.251	.549	.857	.299	.895	.745	.414	.857	.532	.515	.991
Knee	Pre-	94.7 ± 35.0	6.8 ± 40.9	35.4 ± 27.4	6.7 ± 16.4	101.5 ± 26.0	42.1 ± 20.6	111.2 ± 21.8	-0.3 ± 8.7	35.9 ± 23.5	7.3 ± 18.1	111.4 ± 26.1	42.6 ± 18.6
	Post-	107.3 ± 27.6	0.0 ± 8.6	49.6 ± 28.0	4.4 ± 15.5	107.3 ± 31.4	54.0 ± 21.9	106.0 ± 24.3	2.4 ± 5.9	40.3 ± 23.8	5.7 ± 17.6	108.4 ± 24.7	46.0 ± 19.1
	p-Value	.145	.471	.153	.412	.127	.287	.171	.103	.370	.338	.413	.614
Ankle	Pre-	21.8 ± 7.9	16.0 ± 11.6	5.8 ± 7.8	3.1 ± 6.8	37.8 ± 13.0	8.9 ± 7.4	22.4 ± 14.0	15.5 ± 16.5	6.2 ± 4.8	6.4 ± 11.4	37.9 ± 22.5	12.6 ± 11.4
	Post-	18.6 ± 7.5	19.7 ± 11.3	7.4 ± 8.9	2.9 ± 7.6	38.3 ± 12.3	10.3 ± 6.5	15.6 ± 22.7	17.8 ± 24.9	4.6 ± 21.5	6.9 ± 21.3	33.4 ± 9.7	11.5 ± 6.3
	p-Value	.272	**.026***	.655	.994	.210	.601	**.021***	.324	.361	.816	.586	.501

A "+" represents flexion or dorsiflexion; " – " represents extension and abduction. *$p < .05$, **$p < .001$.

Table 6.5 lists the maximum joint angle and range of motion of the lower limbs during obstacle crossing and the statistical analysis the of measures obtained from pre- and post-intervention tests. In participants with PD, the dorsiflexion angle of the leading limb significantly increased to 3.7° (95% CI, -8.98 to -.65; p = 0.03) and the plantarflexion angle of the trailing foot significantly decreased to 6.8° (95% CI, -8.31 to 1.98; p = 0.02) in the post-intervention tests.

4. Discussion

This study aimed to examine the effect of a 12-week online TC intervention on the neuromuscular activity of the lower limb muscles of individuals with PD during obstacle crossing. The proposed biomechanical-based TC program significantly improved the neuromuscular activity of the adductor longus, gluteus medius, tensor fasciae latae, and tibias anterior muscles in people with early-stage PD. The main findings were as follows. 1) The EMG activity in the lower limb muscles during obstacle crossing significantly differed between participants with early-stage PD and HCs from the pre-intervention test. Participants with PD presented significantly higher EMG activity, but only and mostly for peak EMG, but not iEMG, suggesting possibly due a change in the neuromuscular function of the muscles. 2) After the 12-week TC intervention, participants with PD showed significant changes in the EMG activity of the tibialis anterior muscle and the tensor fasciae latae muscle in both limbs or the leading limb and a significant decrease in the peak EMG ratio of the gluteus medius and adductor muscle pairs in the trailing limb. 3) After the intervention, the EMG activity of the gluteus medius and tensor fasciae latae muscles was closer to the level of the HCs and no significant differences were detected. Hence, the TC program improved the neuromuscular activity that is linked to improvements in the movement of ankle and hip joints of people with PD in the ML direction. The alterations of the muscle activity possibly contribute to changes in the gait and postural stability of participants with PD.

The 12-week TC intervention program significantly increased the iEMG ratio of the tibialis anterior in the leading and trialing limbs during obstacle crossing. The role of tibialis anterior is to dorsiflex and invert the foot. This muscle helps increase the stiffness of the ankle joint for better postural stability when standing, particularly in anteroposterior (AP) direction [30], [31]. Aging can lead to co-activation with the gastrocnemius and soleus and cause poor AP postural stability when their balance and posture are challenged [31]–[33]. Some co-activation can be beneficial and provide stiffness in the muscles for a postural response to be generated when the body is perturbed; however, too much may restrict the flexibility and passive motion of the joint, which can be detrimental to stability to be maintained. Therefore, the weak activity of tibialis anterior could change the co-activation of the muscle pair. Evidence shows that PD alters the function of tibialis anterior by delaying the onset time and activation of this muscle [6]. In the early-to-middle stage PD (H&Y 1 to 3), increased rigidity and stiffness in the muscle reduced the activation of the tibialis anterior [5], [34]. Studies in healthy old adults showed that regular TC training shortens the onset latency of tibialis anterior and improves its neuromuscular function [34]–[37]. In the present study, the TC program includes seven TC movements [21]. When performing the seven TC movements, the EMG activity in the tibialis anterior was significantly higher than that during walking. Following the 12-week TC intervention, the iEMG ratio of the tibialis anterior of participants with PD reached levels comparable with the HCs. The increased muscle activity of the tibialis anterior is supported by a significant increase in the dorsiflexed angle in the leading limb during obstacle crossing in the post-intervention test. The observed change in the dorsiflexion angle of the leading limb is due to the improved muscle function. As people with PD have limitations in ankle dorsiflexion during walking [39], [40], TC training would be a good option to strengthen the tibialis and improve the postural stability.

In the pre-intervention test, the iEMG activity of the hip muscles, adductor longus, gluteus medius, and tensor fasciae latae of the leading limb was significantly different between participants with PD and HC. Participants with PD presented significantly higher iEMG ratio in the adductor longus, gluteus medius, and tensor fasciae latae than HCs. After the 12-week TC intervention, the EMG activity of some muscles in participants with PD were significantly improved, such as iEMG ratios of the gluteus medius and tensor fasciae latae. Following the TC training, the significant differences in the EMG activity of the two muscles in the pre-intervention test no longer existed in the two groups. This finding could suggest an improvement in the activity of hip muscles. The role of tensor fasciae latae and gluteus medius is to stabilize the hip and knee joints and maintain mediolateral (ML) postural stability when the body is moving [39]–[43]. Weakness in the hip abductor and adductor muscles is a problem for elderly adults and is related to postural instability [42], which can lead to poor hip-stabilization strategies and increased risk of falls [44], [45]. PD exacerbates postural stability deficits. People with PD show 20% and 14% decreases in hip abductor and adductor force, respectively [3], [45]. Practicing TC gait involves significantly larger hip abduction and heavy involvement of the hip abductors [36]. Performing TC movements, such as Repulse Monkey and Wave-hand in Cloud, uses larger moments and longer peak moment generation of hip extension and adduction [20], [21]. Research in postural stability during obstacle crossing in healthy adults who regularly practice TC showed that they use a larger hip flexion of the leading leg [46] as well as greater hip abduction than regular runners or bikers when crossing over an obstacle [47]. The findings demonstrate the effects of TC training on the hip abductors and adductors in participants with PD. By strengthening the hip abductor and adductor muscles through TC training, people with PD would have improved ML stability of their hip and trunk, which is important for good posture and movement.

In the healthy sex- and age-matched group, performing obstacle crossing led to higher peak EMG and iEMG ratio of the three antagonistic muscle pairs. The ratios for the HCs were higher than that of participants with PD; hence, when the agonist muscles were contracted and its antagonist muscles were relaxed, the generated movement is smooth. Participants with PD had lower ratio of the antagonistic muscle pairs, suggesting rigid muscles. Since the ratio values of their antagonistic muscle pairs were closer to 1.0, this means that activation of their agonist and antagonist muscles was high (i.e., rigidity), which would reduce the smoothness of their lower limb movement. The findings are consistent with published works, in which people with early-stage PD had increased co-activation of the tibialis anterior and medial gastrocnemius during level-ground walking [12], [48]. In the present study, after 12 weeks of TC training, the iEMG ratios of some the antagonistic pairs of participants with PD appeared to return to values comparable with those of HCs. In the PD group, the peak EMG ratios of the gluteus medius and adductor longus significantly changed from 2.13 to 0.54 in the trailing limb following the TC intervention. The pre-intervention value was comparable between participants with PD and HCs (2.13). Participants with PD appear to rely less on the gluteus medius muscle as the activity shifted to the adductor longus after TC training. This finding is unique to the effects of TC training. Thus far, few studies have demonstrated neuromuscular changes after exercise in the PD population [14], [49]–[51]. However, no study examined neuromuscular activity in the hip adductor and abductor muscles and exercise effects.

In the present study, biomechanics analysis of the seven TC movements showed higher hip muscle activity including the tensor fasciae latae, gluteus medius, and adductor longus [21]. The results demonstrated the beneficial effects of the biomechanical-based TC program on hip muscles. Overall, TC training can strengthen hip abductor and adductor muscles and thus improve postural stability at ML direction in participants with PD.

A limitation of this study is the noise in EMG signal. PD causes stiffness in the muscles, resulting in indistinguishable waveform shape. Rigidity in muscles leads to characteristic longer latency reflexes during voluntary contraction as well as larger magnitude and longer duration of muscle activation than in HCs [51]. Upon visual inspection, there was a loss of muscle tone observed in some of the participants with PD possibly because of the effects of pathological aging. The effects of PD seem to affect the magnitude of muscle activation; the magnitude of each burst muscle contraction that was produced varied between trials, in some trial the peak EMG value were low and higher in other trials. The shape of each muscle contraction was not uniform and were not like that of a person without PD, this was possibly due to the increase in muscle rigidity or muscle tone at the time when the movement was generated. Peak normalization of the peak EMG and IEMG values was therefore necessary due to the discrepancy that was observed between trials.

5. Conclusion

The neuromuscular activity of the lower limb, particularly in the hip abductor and adductor muscles, in people with early-stage PD was significantly different from that in age- and sex-matched healthy people during obstacle crossing. The 12-week biomechanical-based online TC intervention significantly benefitted the neuromuscular activity of participants with early-stage

PD. The TC intervention significantly improved the muscle activity of tibialis anterior, tensor fasciae latae, gluteus medius, and adductor longus during obstacle crossing. The training led to the recovery of the muscle activity of the gluteus medius, tensor fasciae latae, and adductor longus of participants with PD to the level comparable with those of HCs. The improved muscle activity in co-contraction of the muscles might suggest the improvement of muscle rigidity. The biomechanical-based TC program could be recommended to people with early-stage PD for management of the neuromuscular function of lower limb muscles.

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CHAPTER 5. GENERAL DISCUSSION AND CONCLUSION

The general goal of the study was to develop a biomechanical-based TC intervention program for people with PD and to examine its effects on gait and postural stability through biomechanical analysis. The specific research purposes were as follows: 1) to develop a biomechanical-based TC program by analyzing the biomechanical characteristics of the selected TC movements; 2) to examine the effects of a 12-week TC intervention program on gait and postural stability in people with PD during obstacle crossing; 3) to explore the neuromuscular effects of TC training on the muscles of the lower limb by analyzing the EMG signals collected from pre- and post-TC intervention tests in the PD participants and healthy controls (HCs). The *General discussion* section is organized based on the specific purposes of the study and research articles generated from this study. First, it aims to discuss the findings from biomechanical analysis of the TC movements. Second, it discusses the effects of TC training on gait and postural stability in people with PD during obstacle crossing. Third, it explains the findings from EMG analysis, including EMG activity in PD participants during obstacle crossing and the changes in the EMG activity following the 12-week TC intervention in the PD participants. Following the general discussion, the study's limitations, conclusion, and considerations for future studies are covered.

5.1 General discussion

Article 1 reported the findings from the biomechanical analysis of seven selected TC movements. Article 2 reported a proposed biomechanical-based TC intervention program for people with PD based on the findings from Article 1. The seven selected TC movements are characterized by multidirectional movements. Compared with walking, most of the selected TC movements presented significantly larger hip flexion and abduction angles and ankle dorsiflexion and abduction angles. Performing the TC movements resulted in significantly larger hip flexion moment, knee flexion and abduction moment, and ankle abduction moment that resulted in stronger EMG signals in the lower limb muscles, indicating stronger muscle activity of the lower limb, particularly in the hip abductor and adductor muscles. The findings suggest that practicing these TC movements required greater joint movement angles of the lower limb and more active muscle activity than walking. The research demonstrated that muscle weakness can lead to postural stability deficiency in elderly people (Ambrose, Paul, & Hausdorff, 2013; Chang et al., 2005; Hilliard et al., 2008; Johnson et al., 2004; Rogers & Mille, 2003). Elderly people prioritized hip strategy to maintain postural stability and exhibited age-related deficit in hip strategy (Amiridis, Hatzitaki, & Arabatzi, 2003), especially in the ML direction (Maki & McIlroy, 2006; Schrager, Kelly, Price, Ferrucci, & Shumway-Cook, 2008). Moreover, people with PD showed 20% and 14% decrease in hip abductor and adductor force, respectively (Johnson et al., 2004; Skinner et al., 2019). Practicing the selected TC movements would be an option for people with PD to improve their hip muscle function. Strengthening the muscles of the hip joint would improve regulation of the pelvis and trunk movements that contribute to postural stability (Allum, Bloem, Carpenter, Hulliger, & Hadders-Algra, 1998; Thorstensson, Nilsson, Carlson, & Zomlefer, 1984). The higher muscle activity in the hip abductors and adductors of the lower limbs during practice of the selected TC movements would have potential effects to improve the function of the muscles. Article 2 provides the details in the selection of the TC movements, the organization of the TC intervention, and data collection procedures. The proposed TC intervention program was unique and novel because it was specifically and purposefully designed for people with PD to improve their postural stability and gait performance. The results from the two articles could fill the research gaps of unavailable information in the TC form selection and TC program formation in the previous related studies (Li et al., 2012; Yang et al., 2015) and could promote knowledge translation from research findings to practice.

Article 3 reported the gait and postural stability changes in people with early-stage PD compared with HCs. Article 4 reported the effects of the 12-week biomechanical-based TC intervention program on gait and postural stability in people with early-stage PD. In addition, the test results from the SLS (with EO and EC conditions) and TUG tests in PD participants and HCs were reported in both articles. Biomechanical analysis of obstacle crossing showed that, compared with HCs, the early-stage PD participants had altered gait indicated by reduced crossing speed and crossing stride length. They exhibited increased crossing width and clearance distance of the heel and toe. Their postural stability was changed, characterized by increased displacement and velocity of the COM and ML separation distance of the COM-COP. Moreover, PD participants had poor performance in the TUG and SLS tests with EO and EC compared with the HCs. The findings are consistent with published studies, the PD participants' gait and postural stability were altered during obstacle crossing (Colnat-Coulbois et al., 2011; Galna et al., 2013; Stegemöller et al., 2012). Aging-related changes in the hip muscles, particularly the tensor fasciae latae and erector spine, influence regulation of backward and lateral movements of the trunk (Dimitrova et al., 2004). This finding is aligned with the current study's findings because weakness in the PD participants' muscles would contribute to poor dynamic postural stability. Galna and colleagues reported that the ML inclination angle of the COM-COP is increased (Galna et al., 2013), the current study's findings further confirm that the PD participants performed obstacle crossing with an increased ML separation distance of the COM-COP. The findings from the current study and Galna and colleagues' study suggest an inability by the PD population to regulate their trunk's motion.

Following the 12-week TC intervention, improvements in the TUG and STS tests suggest that the PD participants' movement capacity and balance have improved. The changes corresponded to improved gait and postural stability during obstacle crossing. The PD participants crossed over the obstacle with a longer crossing stride length and reduced ML COM displacement and velocity, thereby suggesting improved ML stability. They had an increase in crossing stride length of their trailing foot, and increased maximal AP COM displacement, and decreased maximal ML COM-COP separation distance. The longer crossing stride length and reduced ML COM displacement and velocity suggest improved ML stability. The TUG and STS tests showed the same effects as the biomechanics analysis. The findings demonstrate that the 12-week biomechanical-based TC training resulted in changes to gait and postural stability in the PD participants. Some factors that affect postural stability include the strength of the lower limb muscles, proprioception, and the vestibular's function. The beneficial effects of TC training on postural stability are demonstrated in terms of improved proprioception and obstacle crossing performance in healthy older adults (Li et al., 2018; Xu et al., 2004), as well as improved TUG and SLS tests that reflected improved balance and mobility in the PD population (Gao et al., 2014; Li et al., 2012; Zhang et al., 2015). From the analysis of the selected TC movements, performing these movements involved increased loading pattern of the lower limb that was maintained at a higher level and longer-lasting compared with walking. Performing the selected TC movements was multidirectional (Law & Li, 2014; Mao et al., 2004; Wu et al., 2004); the shifting of the COM in different directions could provide special training to improve upright balance and postural stability.

Article 5 reported the EMG study of the lower limb muscles in early-stage PD participants before and after the 12-week TC intervention during obstacle crossing and the comparison of the EMG of the lower limb with that in HCs. Prior to the TC intervention, significant differences were found in the EMG activity of the lower limb muscles during obstacle crossing between the PD participants and HCs. The PD participants presented significantly higher EMG activity in the lower limbs than the HCs. After the 12-week TC intervention, the PD participants showed significant changes in the EMG activity of the tibialis anterior muscle and the tensor fasciae latae muscle in one or both limbs. A significant decrease in the peak EMG ratio of the gluteus medius and adductor muscle pairs in the trailing limb was found, indicating better muscle coordination. The EMG activity of the gluteus medius and tensor fasciae latae muscles was closer to the level of the HCs, and no significant differences were detected. The significant changes in EMG activity of the muscles could be related to the TC training that required higher muscle activity, as reported in Article 1. Four of the seven selected TC movements were dynamic movements. The EMG activity during the performance of these movements was significantly higher, ranging from 0.3 to 6.1 times of EMG in walking, in the pairs of flexors/extensors of hip, knee, and ankle. The role of tibialis anterior is to dorsiflex and invert the foot. This muscle increases postural stability of the ankle joint, particularly in the AP direction. Following the 12-week TC intervention, the increase in muscle activity of the tibialis anterior corresponded to an increase in dorsiflexed angle in the leading limb during obstacle crossing. TC training would be a good option to strengthen the tibialis anterior and improve postural stability because people with PD have limitations in ankle dorsiflexion during walking (Kim et al., 2012; Sofuwa et al., 2005). The role of tensor fasciae latae and gluteus medius is to abduct the hip and to stabilize the hip and knee joints, as well as maintain ML postural stability when the body is moving (Chang et al., 2005; Porto, Junior, Magnani, & Abreu, 2015; Winter, 1995). TC training involves using a larger hip flexion of the leading leg (Chang, Huang, & Chang, 2015), and hip abduction was greater in people who regularly practice TC than regular runners or bikers when crossing over an obstacle (Li, 2016). The findings demonstrate the effects of TC training on the hip abductors and adductors in the PD participants, thereby improving the ML stability of their hip and trunk to achieve good posture and movement. Furthermore, the reduction in muscle co-contraction might suggest a reduction in the motor-related symptoms of PD, such as muscle rigidity. This finding is important because this study is the first to investigate the neuromuscular changes in the muscles that are responsible for the improvements in the ML postural stability of early-stage PD participants.

This study has answered the research questions and realized the proposed research goal. The selected TC movements were suitable because they are easy to learn; performing these movements involved larger hip abduction and ankle dorsiflexion angles than walking to strengthen the gluteus medius and tibialis anterior muscles. The biomechanical-based TC intervention was effective because the PD participants significantly improved their gait and postural stability. The possible mechanism is related to the neuromuscular effects of TC training particularly in the tibialis anterior and gluteus medius. These muscles were responsible for maintaining AP and ML postural stability during obstacle crossing.

5.2 Limitations

Participants in the physical activity group

In the original design of the study (Article 2), a single blind randomized control trial should have been conducted to compare the effects of a TC program with a physical activity (PA) routine. The PD participants should be randomized to the TC or PA group. The study should be conducted for 12 weeks (three months), and the primary and secondary measures should be assessed at baseline and at 6 and 12 weeks. The participants in the PA group formed the controls; however, their data were excluded in the analysis of gait and postural stability as well as EMG study (Articles

4 and 5). The target sample for the PA group was not reached (n = 15). Only the data of five participants were obtained following the PA intervention (please refer to appended data in the *Appendix* section). The main reason was the COVID-19 restriction. Recruiting sufficient participants to complete this set of data within a reasonable timeframe was impossible.

Proposed measures & intervention program

The three executive function cognitive assessments (Stroop Test, Trail Making Test- Part B, and the Wisconsin Card Sorting Test) could not be included because there was not enough time to collect the required amount of data. Consequently, comparison of the measures between the TC and PA groups was impossible because the number of participants in TC and PA groups was unequal (n = 15 in TC, n = 5 in PA) and no statistical tests were performed. The biomechanical-based TC intervention program was offered online instead of in-person, which was originally planned, due to the Covid-19 pandemic. Certainly, online intervention could have limited the social interaction and communication between the participants (Alberts et al., 2021; van der Kolk et al., 2019; Mañago et al., 2021). Despite the limitations with the online training format, the intervention program was greatly successful and demonstrated its significant and meaningful effects on gait, postural stability, and neuromuscular function of the lower limb in the population.

5.3 Conclusion

This study investigated the effects of the online biomechanical-based TC intervention program on gait and postural stability in people with early-stage PD. The study included two experiments: first, to develop a biomechanical-based TC intervention by analyzing the kinematics, kinetics, and EMG activity of the lower limbs during performance of a selected TC movements by an experienced TC master; second, a biomechanical analysis of the gait and postural stability as well as neuromuscular activity of the lower limb during obstacle crossing before and after 12-week TC intervention in people with early-stage PD. Based on the findings from the two experiments, the following conclusions are drawn:

1) The biomechanical-based TC program is effective. The TC program included seven selected TC movements, four dynamic TC movements (Brush Knee and Twist Step, Repulse Monkey, Wave-hand in Clouds, and Lateral Forward Step), and three static TC movements (Starting Form, Hero Touch Sky, and Push Hand Back), characterized by 3D movements, large joint movement angles of the lower limbs, large flexion and abduction moments in the hip joint, and higher muscle activity of the lower limb, particularly in the hip abductors and adductors.

2) Compared with age- and sex-matched HCs, the early-stage PD participants demonstrated gait and postural changes. They presented a decreased crossing speed with increased hip abduction and knee adduction of the trailing limbs during obstacle crossing. Moreover, their body's ML postural stability was decreased, suggesting altered dynamic postural stability.

3) The neuromuscular activity of the lower limb in the early-stage PD participants were altered compared to the HCs. The changes are presented as increased muscle activity of

the tibialis anterior, hip abductor, and adductor muscles during obstacle crossing. The PD participants had larger magnitude and longer duration of muscle activation than the HCs, indicating altered neuromuscular function and activity of their muscles during obstacle crossing.

4) The online biomechanical-based TC intervention program (60 min each session, three sessions per week, over a 12-week period) is effective. This finding was demonstrated by: a) decreased motor-related symptoms of PD as indicated by UPDRS-III score, and improved movement and mobility as indicated by a faster completion time on the timed-up-and-go test, b) improved gait indicated by an increase in crossing stride length of their trailing foot, and c) improved dynamic postural stability that was indicated by a low toe clearance height, an increased maximal AP COM displacement, and a decreased maximal ML COM-COP separation distance after TC training. The evidence suggests improved capacity to control their body's motion and posture.

5) The mechanisms of TC's beneficial effects are related to the neuromuscular changes in the lower limb muscles that were observed after TC training. The TC intervention significantly improved the muscle activity of the tibialis anterior, tensor fasciae latae, gluteus medius, and adductor longus during obstacle crossing. The training led to recovery of muscle activity of the gluteus medius, tensor fasciae latae, and adductor longus muscles to levels comparable to the HCs.

6) The biomechanical-based TC intervention program could be an exercise option for people with early-stage PD to improve the gait, postural stability, and neuromuscular function of the lower limbs. It is feasible, practical, and effective.

5.4 Considerations for future study

For future studies, some studies could be considered. First, a between-group comparison could be performed with a completed set of data for PD group and physical activity (PA) groups. TC intervention effects were only examined in the PD group by the pre- and post-intervention tests in the current study. Examining the pre- and post-intervention changes in the PA group would explain the effects of PA and compare with the effects of TC training. Furthermore, the effects of the TC intervention on the neuromuscular activity in the upper limbs, neck, and trunk should be studied because these muscles are associated with postural stability (Wang et al., 2017; Zhou et al., 2015). The study findings could provide information about the effects of TC training on the muscle's function following TC training. Lastly, the effects of the TC intervention for improving gait and postural stability of the PD people have not been compared with other forms of exercise, such as resistance, aerobic, treadmill, and multimodal training (Landers et al., 2019; Schlick et al., 2015; Vieira-Yano et al., 2021). This comparison could identify the appropriate forms of exercise for people with PD and connecting these data to these individuals would help inform them of the potential benefits of each type of exercise on their health and wellbeing.

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APPENDIXES

Table 7.1: Major findings of past Tai Chi training studies involving people with PD.

Studies	Training period and frequency, weeks (days per week)	Outcomes (% change from baseline with between-group difference)				
		Disease severity	**Muscle Strength**	**Aerobic capacity**	**Balance performance**	**Gait performance and mobility**
Vergara-Diaz et al. (2018)	24 (2)	NS	NA	NA	NA	NS
Zhang et al. (2015)	12 (2)	NS	NA	NA	NS	Gait velocity: tai chi 13%
Gao et al. (2014)	12 (3)	NS	NA	NA	BBS: tai chi 9%	NS
Kim et al. (2014)	12 (3)	NA	NA	NA	NA	*Swing limb* AP & ML COP dis.: 24 & 33%, respectively
Amano et al. (2013)	16 (2)	NS	NA	NA	NS	NS
Choi et al. (2013)	12 (3)	UPDRS-III: tai chi -43%*	NA	NS	NA	NS
Li et al. (2012)	24 (2)	UPDRS-III: tai chi -42%*	Knee: tai chi 16-22%	NA	Max. excursion: tai chi 15% FRD: tai chi 20%	Stride length: tai chi 8% Gait velocity: tai chi 10% TUG: tai chi -12%
Kim et al. (2011)	12 (3)	NA	NA	NA	NA	*Swing limb* AP & ML COP dis.: 21 & 35%, respectively

AP = anteroposterior; COP = center of pressure; dis. = displacement; FRD = functional reach distance; ML = mediolateral; NA = data not available; NS = nonsignificant effect. *Changes exceed respective moderate clinical important difference: UPDRS-III = 5.2 points. Adapted from past review publication (Mak et al., 2017).

Supplemental data from Study#4: 12-week intervention, physical activity group (*n* = 5)

The participants in the physical activity (PA) group (*n* = 5, mean age: 73.2 ± 5.7, mean disease duration: 6.0 ± 3.0, H&Y stage 1 to 2, mean: 1.4 ± 0.5) were asked to maintain their regular physical activity or exercise over a 12-week period. During this period, the participants were instructed to engage in at least 60 minutes of regular physical activity on their own, three times weekly. Regular physical activity may include such activities as walking, cleaning, or performing chores inside the home, and/or climbing the stairs; no restrictions were made to limit others forms of physical activity or exercise; the control group was permitted to engage in organized sports, instructor-led class such as boxing, dance, etc. to ensure that enough participants could be recruited. The participants in this group were asked to complete an activity log or journal to monitor their regular physical activity levels.

Pre- and post-intervention assessment

Similar to the tai chi group, the participants in the PA group visited the lab at baseline and 12-weeks after the start of the intervention. They were assessed while they were clinically on, or fully responding to their medication (~1-2.5h after their last medication dose). The general cognitive function of the participants was assessed using the Montreal Cognitive Assessment (MoCA).

After outfitting the participants with reflective markers, the participants were asked to perform five trials of obstacle crossing. Additionally, they were assessed with the timed-up-and-go test and single-leg stance (SLS) test with eyes open (EO) and closed (EC).

Results

As reported in Table 7.2 below, no significant changes were observed in PA group for UPDRS-III, SLS with EO and EC scores, and TUG pre- and post-intervention. There were also no meaningful changes in the obstacle clearance and dynamic postural stability variables.

Discussion

Due COVID-19 pandemic that affected the data collection process of this study, pilot testing work that was planned to be conducted between the months of January to May 2020 was delayed for several months, which was to part of the proposed thesis work. In-person access to the lab and office with resumption of participant testing in the lab early September 2021 permitted some research and laboratory work to be completed during this time. The data collection for this study formally began early November 2021 and was completed April 2022. In total, the data from 21 healthy older adult participants were collected (12 females, 10 males), 18 participants with early-stage PD (H&Y 1 to 2; 8 females, 11 males), of which 17 were randomly allocated to the TC group and 5 to the PA group. Note: the participants who were randomized to the PA group first completed 12-week PA intervention before commencing the TC intervention.

No significant changes were observed in the clinical measures that were collected pre- and post-intervention for the PA. There were some trends towards improvement in the obstacle clearance and dynamic postural stability variables in the PA group, however these trends were not significant. The participants in the PA group were physically active; on average as a group, they exercised 34.0 ± 22.2 minutes/session for 4.0 ± 2.2 days/week. These lengths of each session were shorter compared to the tai chi group but the frequency per day was comparable (52.4 ± 13.7 minutes/session, 4.1 ± 1.1 days/week). Only five participants were collected for the PA group due time constraints in the data collection, it was not feasible or possible to obtain a complete set of data for this group. The study's target number of participants for each group was 15 participants (n = 30). Comparisons between the TC and PA groups could not be completed, however is possible that future studies or Masters/PhD project could extend this study data collection procedures and protocol such that this could be made possible.

Table 7.2. Mean and SD of the clinical tests, gait, foot clearance, center of mass (COM) and center of pressure (COP) related variables for the physical activity group (*n* = 5).

Assessment	**Pre-intervention**	**Post-intervention**	**Change**	***P* Value**
Clinical				
UPDRS-III	10.7 ± 9.0	15.0 ± 1.0	4.3 ± 9.9	.526
Timed Up-and-Go	12.0 ± 3.2	12.3 ± 3.2	0.1 ± 0.5	.742
Single leg standing with eyes open	10.0 ± 3.3	12.0 ± 3.9	2.3 ± 5.3	.991
Single leg standing with eyes closed	4.8 ± 1.3	2.5 ± 0.6	-1.6 ± 0.6	.152
Gait variables				
Gait speed (m/s)	0.98 ± 0.15	0.99 ± 0.12	0.01 ± 0.1	.758
Crossing speed (m/s)	0.91 ± 0.15	1.01 ± 0.40	0.09 ± 0.45	.213
Crossing stride length of LF (m)	1.34 ± 0.14	1.38 ± 0.13	0.03 ± 0.14	.218
Crossing stride length of TF (m)	1.40 ± 0.15	1.42 ± 0.11	0.02 ± 0.10	.435
Crossing step length (cm)	61.8 ± 8.6	63.6 ± 9.3	1.8 ± 10.2	.136
Crossing step width (cm)	6.8 ± 3.9	6.1 ± 5.1	-0.7 ± 4.6	.215
Toe clearance distance of LF (cm)	18.2 ± 2.0	19.0 ± 3.7	0.8 ± 3.2	.579
Heel clearance distance of LF (cm)	12.9 ± 2.0	14.1 ± 3.4	1.3 ± 3.7	.875
Pre-horizontal distance of TF (cm)	25.8 ± 5.3	26.8 ± 6.1	0.8 ± 5.7	.316
Post-horizontal distance of LF (cm)	18.7 ± 4.1	19.8 ± 4.5	1.1 ± 4.5	.282
COM, COP related variables				
Max AP COM displacement (cm)	141.5 ± 12.9	143.5 ± 11.8	2.0 ± 10.3	.477
Max ML COM displacement (cm)	9.9 ± 2.2	7.9 ± 3.0	-2.0 ± 10.3	.535
Max AP COM velocity (cm/s)	117.3 ± 15.7	119.7 ± 13.4	2.5 ± 10.5	.398
Max ML COM velocity (cm/s)	24.7 ± 4.3	20.8 ± 6.4	-3.9 ± 5.0	.592
Max AP COM-COP separation (cm)	30.6 ± 4.1	35.0 ± 8.5	2.7 ± 11.6	.989
Max ML COM-COP separation (cm)	8.8 ± 2.7	9.8 ± 6.3	1.0 ± 5.3	.174

AP: anterior-posterior, COM: center of mass, COP: center of pressure, LF: leading foot, max: maximum, min: minimum, ML: medial-lateral, PA: physical activity, SD: standard deviation, TC: tai chi, TF: trailing foot. *p < .05 & **p < .001.

25/10/2019

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CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-01-19-2284
Titre du projet / Project Title	The Effects of Tai Chi Intervention on Postural Stability and Gait in People with Parkinson's Disease
Type de projet / Project Type	Recherche de professeur / Professor's research project
Statut du projet / Project Status	Approuvé / Approved
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	25/10/2019
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	24/10/2020

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Jing Xian LI	École des sciences de l'activité physique / School of Human Kinetics	Chercheur Principal / Principal Investigator
Nok-Yeung LAW	École des sciences de l'activité physique / School of Human Kinetics	Co-chercheur principal / Co-principal investigator
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Conditions spéciales ou commentaires / Special conditions or comments

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25/10/2019

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Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout évènement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completedfour weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Riana MARCOTTE
Responsable d'éthique en recherche / Protocol Officer
Pour/For **Daniel LAGAREC** Président(e) du/ Chair of the **Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board**

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École des sciences de l'activité physique
Faculty of Health Sciences
School of Human Kinetics

Consent Form

Title of the study: The Effects of Tai Chi Intervention on Postural Stability and Gait in People with Parkinson's Disease

Principal Investigator: Jing Xian Li ____________________, PhD
Associate Professor
School of Human Kinetics, Faculty of Health Science
University of Ottawa

Co-Investigator: Nok-Yeung Law ____________________, M.Sc.
PhD Candidate
Human Movement Biomechanics Laboratory
University of Ottawa

INVITATION TO PARTICIPATE:
I am invited to participate in the above-mentioned research testing conducted by Dr. Jing Xian Li of the School of Human Kinetics, Faculty of Health Sciences, University of Ottawa. The research is entitled "The Effects of Tai Chi Intervention on Postural Stability and Gait in People with Parkinson's Disease (PD)." The purpose of the research is to study the effects of tai chi intervention on gait and postural stability in those with PD.

ELIGIBILITY:
To be able to participate in this study, I must be between ages of 50 to 75 years. I must be diagnosed with Parkinson's disease, severity ranging from stage 1 to 3 on the Hoehn & Yahr scale. I must not have any motor fluctuations as measured by the Unified Parkinson's Disease Scale, motor sub-score (UPDRS-III). I must have stable medication use and be able to stand and walk independently. I must be available to attend or engage in physical activity 3 times/week for a 12-week period. I must not be enrolled in any other behavioral, pharmacological study or instructor led exercise programs during the duration of the study. I must not demonstrate mild cognitive impairment (mini-mental state examination < 24), have poorly cardiovascular disease symptoms during moderate exercise, poorly controlled hypertension, and any debilitating conditions that would prevent myself from engaging in physical activity for at least 60 minutes.

PROTOCOL:
I will randomly be assigned to either groups: tai chi or physical activity.

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If I am enrolled in the tai chi group, I will be taught tai chi in a class size of 5 to 12 students offered in the laboratory or community center, by a certified tai chi instructor. Each tai chi class will be 60 minutes, offered 3 times per week. I am encouraged to attend at least two sessions per week for up to 12-weeks. To facilitate learning of the movements, I will be given a hard copy of the illustrated 6-form tai chi program or a 5 to 10-minute demonstration video with the instructor.

If I am enrolled in the physical activity group, I will be required to engage in at least 60-minutes (3 times per week for 12 weeks) of regular physical activity on their own that will be documented in an activity log or journal. Some types of activities I will be allowed to engage in will include walking, jogging, stair climbing, or light stretching.

PARTICIPATION:
I will attend three sessions of test at the Human Movement Biomechanics laboratory, 200 Lees Avenue, University of Ottawa. The test will be at the beginning, 6, and 12 weeks after commencing either exercise programs, such as tai chi or regular physical activity. I will have to complete and return a form of my exercise or physical activity practicing activity every month for monitoring purposes. For my neuropsychological assessment, I will allow the researcher to assess my cognitive functioning using three commonly used neuropsychological assessment tests. During my movement assessment, I will wear shorts and a shirt that will be provided for motion capture and have small reflective markers placed on chosen anatomical landmarks on my body. I will have pairs of electrodes attached on my limbs for electromyography analysis. My body weight and height will be measured. My movement while walking and during obstacle crossing will be recorded using a 3-dimensional video recording system. I will perform 5 trials for each of type of movements, respectively. The data collection session will last about 2 hours.

RISKS:
There are no risks involved. The researcher has assured me that I will have enough time to practice crossing over the obstacle and warmup before formal data collection and I may request to stop at any time if I need to rest. In any case I am not able to keep my balance under these conditions I can withdraw from the study. The researcher has assured me that if there is any lingering discomfort, I can withdraw from the study at any time.

DISADVANTAGES OF PARTICIPATING:
I understand the primary disadvantage of participation will be the time required to complete and to perform data collection.

BENEFITS:
I will not benefit directly from my participation. However, I will gain a better understanding on my exercise engagement and physical activity performance. I will be able to learn how my

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participation in an exercise program and/or regular physical activity affect my physical capacity and wellbeing. My contribution in this research will be beneficial for the understanding of the effects of exercise in those with Parkinson's disease.

CONFIDENTIALITY AND CONSERVATION OF THE DATA:
I understand that the data collected from me will be used only to serve the research's purpose and data might be used in student theses and my confidentiality will be ensured. I will be assigned an anonymous identification code that will be used throughout the research. The data (completed consent forms, testing notes, and measurement recordings in paper form) will be stored in a locked filing cabinet in the office of the researcher at the University of Ottawa. The electronic data will be kept in the computer of the researcher and will be password protected. Only the researchers will have access to the data. I understand that any published results will be presented with complete anonymity.

The data will be conserved for a period of 5 years after the time of publishing the research results, at which time the electronic data will be deleted, and the printed data will be shredded.

ANONYMITY:
Anonymity will be assured in the following manner: a code number system will be employed during the data collection, analysis, and reporting. I will not be identified in any reports or publications.

COMPENSATION:
I will receive $15.00 at the beginning of the session of evaluation of my postural stability and movement capacity to help cover my travel and parking costs. After the study has begun if I choose to withdraw, I can still receive the compensation. A simple meal will also be provided with to a maximum of $15 if the biomechanics assessment goes over regular mealtime (lunch or dinner).

VOLUNTARY PARTICIPATION:
Participants who choose to withdrawal from the study will also be given the opportunity to withdraw their data.

I understand that I may ask questions regarding this study at any time and they will be answered. These questions may be addressed to Dr. Jing Xian Li.

MORE INFORMATION ABOUT THIS STUDY:
If I have any questions with regards to the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa at Room 154, Tabaret Hall 550 Cumberland Street, Ottawa, ON, K1N6N5, or (613) 562-5387 or ethics@uottawa.ca.

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Faculty of Health Sciences
School of Human Kinetics

CONSENT:
I declare that I understand this project, the nature and degree of my participation and possible disadvantages and risks listed in this consent form. I have had the opportunity to ask all my questions concerning the different aspects of the study and have received responses to my satisfaction.

I voluntarily agree to participate in this study.

I agree that Dr. Jing Xian Li can keep my name and telephone number for contact me for any future study that she may be carrying out.

Yes _________ **No_________**

There are two copies of this consent from one of which is for me to keep.

____
Name of Participant

____________________________ ____________________________
Signature of Participant Date

____________________________ ____________________________
Signature of Researcher Date

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