BALANCE CONTROL: USING MOTOR BEHAVIOR CONCEPTS AS TOOLS FOR ASSESSING AND MODIFYING POSTURAL ADJUSTMENTS

By

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ABSTRACT

Balance control is an essential component of standing balance that enables individuals to adopt various postures, react to external perturbations and use anticipatory postural adjustments (APAs) that precede voluntary movements. Impairment to balance control increases the likelihood of falls. Falls are a significant health concern in Canada, especially among older adults and people post-stroke. The increased risk of falling indicates that there is a great need for better understanding of risk factors related to falls and establishing methods for assessing and modifying those risks.

Falls occur as a result of compounding factors that combine and overwhelm an individual's ability to maintain or regain his or her balance. However, there is ample evidence to suggest that APAs impairment leads to greater likelihood of falls. The field of motor control and learning offers knowledge that can be utilized for researching balance control and postural adjustments. Motor control and learning concepts such as Fitts' law, focus of attention and the challenge point framework (CPF) can be used to provide important information related to assessing and modifying postural adjustments.

This document is a manuscript-style thesis that includes three studies. This thesis contributes to the literature by providing a knowledge synthesis of studies related to the use of motor behavior concepts among balance control studies. The results of the scoping review suggest that the CPF is a useful method for designing a progressive therapeutic program. Fitts' law can be used for adjusting the difficulty of balance control tasks. Focus of attention studies indicate that adopting an external focus of attention improves performance during standing balance tasks. Further, this thesis provides preliminary evidence related to the use of motor behavior concepts for improving and assessing APAs. Two studies investigated the effects of

adopting different foci of attention among different populations when performing a lower extremity Fitts' task. The results of both experimental studies suggest that when performing a lower extremity Fitts' task, adopting an external focus of attention yields better performance among young and older adults and people post-stroke. Moreover, the Fitts' task used in the studies can distinguish between APAs for different populations (e.g., older and young adults). The beneficial effects of adopting an external focus of attention during postural control tasks could be effective in improving balance control and reducing the risk of falls among individuals with balance impairments (e.g., people post-stroke).

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DEDICATION

This thesis is dedicated to my parents.

For their endless love, support and encouragement.

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LIST OF ABBREVIATIONS

A	Amplitude of movement (Fitts' law)
ADL	Activities of daily living
ANOVA	Analysis of variance
AP	Anteroposterior
APAs	Anticipatory postural adjustments
APA_D	Anticipatory postural adjustment duration
APA_M	Anticipatory postural adjustment magnitude
BMI	Body mass index
BOS	Base of support
CB&M	Community balance and mobility scale
cm	Centimeter
CMSA	Chedoke-McMaster Stroke Assessment
COM	Center of mass
COP	Center of pressure
CPAs	Compensatory postural adjustments
CPF	Challenge point framework
EEG	Electroencephalography
EFA	External focus of attention
EMG	Electromyography
GMP	Generalized motor program
GSH	General slowing hypothesis
ID	Index of difficulty (Fitts' law)
$Integ_{EMG100\text{-}400}$	Integral of EMG activity from 100 to 400 milliseconds
$Integ_{T0EMG\text{-}T0}$	Integral of EMG activity from onset of EMG activity to onset of movement
IFA	Internal focus of attention
KR	Knowledge of results
KT	Knowledge translation
MeSH	Medical Subject Headings
ML	Mediolateral

mm/s	Millimeter/second
ms	Milliseconds
MT	Movement time
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
PAR-Q	Physical Activity Readiness Questionnaire
PHAC	Public Health Agency of Canada
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Peak velocity
RCT	Randomized controlled trial
RMSE	Root mean score error
RT	Reaction time
SD	Standard deviation
SD_T	Variability at target
SENIAM	Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles
SO	Soleus muscle
T_0	Movement onset time
T_{0_EMG}	Onset of EMG activity
TA	Tibialis anterior muscle
T_{END}	Movement end time
ttPV	Time to peak velocity
W	Width of target (Fitts' law)
WFQ-R	Waterloo Footedness Questionnaire – Revised
WHO	World Health Organization
y	Years

CHAPTER 1: INTRODUCTION AND RATIONALE

1.1. Introduction

Balance control, which is defined as the ability to keep the center of mass (COM) within the base of support, is a fundamental component of standing balance (Shumway-Cook & Woollacott, 2012). The control of posture and balance requires complex interplay between the sensory, cognitive and motor systems in order to adopt various postures, react to external perturbations, and use anticipatory postural adjustments (APAs) that precede voluntary movements (Marsh & Geel, 2000; Orrell, Eves, & Masters, 2006; Walker, Brouwer, & Culham, 2000; Woollacott & Shumway-Cook, 2002; Zech et al., 2010). An impairment to balance control is associated with an increased risk of falling (Chang et al., 2004; Muir, Berg, Chesworth, Klar, & Speechley, 2010; Sherrington et al., 2008).

Falls are a significant health concern in Canada, especially among older adults. Falls are the leading cause of injury and hospitalization among Canadian seniors, accounting for over 85% of all injury-related hospitalizations (Public Health Agency of Canada [PHAC], 2014). Falls are also the leading cause of injury during the course of health care delivery in long-term care, home-care, and acute-care settings (PHAC, 2014). The high prevalence of falls contributes to a significant burden on the healthcare system due to the resulting need for additional services, the occurrence of falls-related complications, and increased lengths of stay. Direct health care costs for falls in Canada are estimated at $2 billion annually (PHAC, 2014).

In addition to older adults, people post-stroke also have an increased risk of falling. Stroke is the leading cause of adult disability, with over 405,000 Canadians living with the effects of stroke (Lindsay et al., 2014). Among the various impairments that may be caused by stroke, impaired balance control is likely to have the greatest impact on independence and gait (Bohannon & Leary, 1995; Fong, Chan, & Au, 2001; Geurts, de Haart, van Nes, & Duysens, 2005; Keenan, Perry, & Jordan, 1984; Sandin & Smith, 1990). Further, postural control impairment is a major health problem among individuals post-stroke and leads to a high incidence of falls both during the rehabilitation phase and thereafter (Alemdaroglu, Ucan, Topcuoglu, & Sivas, 2012; Forster & Young, 1995; Weerdesteyn, de Niet, van Duijnhoven, & Geurts, 2008). Therefore, it is important to exhaustively understand postural control, and all of its components, in order to establish methods to prevent falls, fear of falling and subsequent impairments in postural adjustments among older adults and people post-stroke.

The field of motor learning and control offers knowledge that can be utilized for researching balance control and postural adjustments. Further, the field of motor learning and control has already influenced clinical practice (Magill & Anderson, 2014; Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012). For example, the classic motor program theory put forward by Henry and Rogers (1960) led to several subsequent iterations of the motor program theory, which have allowed rehabilitation clinicians to move beyond a reflex explanation for disordered motor control (Henry & Rogers, 1960; Klapp, 2010; Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012).

Another example related to the influence of the motor control and learning field on clinical practice is the research involving the effect of contextual interference on learning, retaining and transfer of motor skills (Shea & Morgan, 1979). The work by Shea and Morgan (1979) provides evidence that utilizing a random practice routine (changing practice deliberately to make practice more cognitively challenging) yields better learning of a motor skill than a blocked practice routine (repeating the same task in the same context for the duration of practice, making practice cognitively more simple). Their finding, also supported by subsequent studies, has led clinicians to utilize conditions leading to high contextual interference (challenging practice conditions) for the training of motor skills (Brady, 2008; Shumway-Cook & Woollacott, 2012).

In addition to the previous examples of motor behavior theories, there are three concepts of motor behavior that are also utilized in clinical practice, which are Fitts' law, focus of attention theory and the challenge point framework (CPF) (Fitts, 1954; Fitts & Peterson, 1964; Guadagnoli & Lee, 2004; Wulf, Höß, & Prinz, 1998). These two theories and one framework represent seminal landmarks of the field of motor control and learning (Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012). Further, Fitts' law, focus of attention and CPF can provide useful insights for researching balance control and postural adjustments among individuals with balance impairments (e.g., older adults and people post-stroke).

1.1.1. Rationale for the Thesis

While the aforementioned theories and framework of motor behavior have been published for some time (Fitts, 1954; Guadagnoli & Lee, 2004; Wulf et al., 1998), and they have been used in clinical studies related to balance control, major knowledge gaps have been identified following the examination of the literature citing these concepts. First, the body of evidence lacks a knowledge synthesis that examines the use of the previous motor control and learning theories in balance control studies. A review of the current literature that involves Fitts' law, CPF and focus of attention among studies related to balance control would provide a comprehensive look at the existing evidence. Further, a knowledge synthesis of studies would help clarify and substantiate the usefulness of these motor behavior concepts in balance control and identify possible knowledge gaps or research ideas to guide future studies.

Another important finding when examining the literature is that only a few studies have been conducted to investigate Fitts' law during aiming movements with the lower extremity and how it is linked to APAs (Bertucco & Cesari, 2010; Bertucco, Cesari, & Latash, 2013; Danion, Duarte, & Grosjean, 1999; Duarte & Freitas, 2005; Duarte & Latash, 2007; Juras, Slomka, & Latash, 2009). In these studies the authors report that measures of APAs (e.g., APAs duration and amplitude) scaled with the parameters of a Fitts' law task (i.e., amplitude and width). Utilizing Fitts' law to investigate APAs is advantageous as it can control the level of task difficulty; and APA parameters are predictable when participants performed a Fitts' task. However, in all of the previous studies the participants were young adults, and the studies did not include participants in several age groups. Also, participants who have neurological disorders that are associated with balance impairments and have a higher risk of falling have not been involved in studies investigating APAs during a Fitts' task.

Despite the previous research related to APAs, methods for improving APAs are limited (Aruin, 2016; Aruin, Kanekar, Lee, & Ganesan, 2015; Silva et al., 2018). Further, no previous study has utilized concepts from the literature of motor behavior in order to propose new approaches for improving APAs. For example, studies related to focus of attention did not investigate if APAs show change when adopting different attentional foci. Given the importance of APAs in postural control (Aruin, 2016; de Azevedo, Claudino, Conceicao, Swarowsky, & Santos, 2016; Kanekar & Aruin, 2014b), it is vital to develop methods for assessing and improving APAs, especially among individuals with balance impairments.

It is imperative that the evidence and concepts gleaned from previous research is tested and applied to clinical populations in order to implement the best available evidence into clinical practice (Straus, Tetroe, & Graham, 2013). Therefore, the overall objective of this document is to: (i) address the lack of a knowledge synthesis examining the use of the motor behavior theories/framework in balance control studies, (ii) enhance the understanding of APAs during a lower extremity Fitts' task, and how APAs are related to focus of attention; and (iii) investigate APAs and how they relate to focus of attention among a population who are known to have a high risk of falls (i.e., older adults and stroke).

1.2. Thesis Summary and Organization

This document is presented as a manuscript-style thesis and is divided into five chapters. In the present chapter, I provide an introduction and rationale for the thesis followed by a literature review on postural control and APAs. Subsequently, I describe theories, models, laws and frameworks in order to differentiate them. Finally, I discuss these three motor behavior concepts: Fitts' law, focus of attention and challenge point framework. Chapter two provides a scoping review manuscript of motor behavior concepts in the study of balance. Chapter three is an experimental study comparing APAs between young and older adults while performing a lower extremity Fitts' task and the effect of different foci of attention. Chapter four is another experimental study investigating the effects of different attentional foci on APAs among people post-stroke while performing a lower extremity Fitts' task. The work in chapters two, three and four are presented as they were submitted for consideration for peer-reviewed journal publication. Chapter five provides a summary of key research findings, as well as discussion around clinical implications of these findings. I discuss current gaps in knowledge and possible directions for future work.

1.3. Literature Review

1.3.1. Postural Control

Postural control involves controlling the body's position in space for maintaining stability and orientation. It is defined as the ability to maintain an appropriate relationship between the different body segments and between the body and the environment for a task (Shumway-Cook & Woollacott, 2012). The ability to control the body's position in space is fundamental for many motor tasks. However, the requirements for stability and orientation vary depending on the task and the surrounding environment (Shumway-Cook & Woollacott, 2012). For example, quiet standing involves maintaining the stability by controlling the COM within the base of support (BOS). Also, orientation of head and eyes and other body parts must be maintained to an appropriate task-specific orientation. Postural control emerges from the interaction of many systems. Among these systems are anticipatory and compensatory mechanisms that are utilized for optimizing postural control. These mechanisms are essential for postural control and stability and are discussed in detail below.

1.3.1.1. Anticipatory and Compensatory Postural Adjustments. Anticipatory postural adjustments (APAs) and compensatory postural adjustments (CPAs) are two essential components of standing balance. Anticipatory postural adjustments are changes in the activity of postural muscles prior to voluntary movements in order to maintain vertical equilibrium. These APAs occur 80-100 milliseconds (ms) prior to a movement and are generally thought to generate forces and moments directed against perturbations associated with voluntary actions. Studies have shown that APAs depend on movement velocity and on the inertial load of an upcoming movement (Massion, 1992). The overall goal of APAs are to maintain the position of the body's COM prior to a forthcoming body perturbation to minimize the danger of losing equilibrium

(Massion, 1992). On the other hand, CPAs are muscle responses and body movements after postural perturbations and they serve to minimize the destabilizing effects caused by postural disturbances (de Azevedo et al., 2016; Nashner & McCollum, 1985). The goal of CPAs is to restore the position of the COM after a perturbation has already occurred (de Azevedo et al., 2016; Nashner & McCollum, 1985).

The effective use of both APAs and CPAs is essential for postural control in humans (Aruin, 2016; de Azevedo et al., 2016; Kanekar & Aruin, 2014b). When encountering an unexpected perturbation, CPAs are the main mechanism used by the body to restore equilibrium (Aruin, 2016; de Azevedo et al., 2016; Kanekar & Aruin, 2014b). However, when a perturbation is expected, APAs are the first line of defense for postural control and then they are followed by CPAs to aid in completing the process of maintaining balance (Aruin, 2016; de Azevedo et al., 2016; Kanekar & Aruin, 2014b). Therefore, utilizing APAs reduces the need for requiring large CPAs and leads to greater postural stability. The importance of APAs becomes even more significant when considering older adults or individuals with neurological impairments such as stroke or Parkinson's disease. Older adults and people with neurological impairments show deficits in APAs, which requires them to rely primarily on CPAs for postural control (Bazalgette, Zattara, Bathien, Bouisset, & Rondot, 1987; Bleuse et al., 2008; Garland, Stevenson, & Ivanova, 1997; Hedman, Rogers, Pai, & Hanke, 1997; Horak, Esselman, Anderson, & Lynch, 1984; Inglin & Woollacott, 1988; Jacobs, Lou, Kraakevik, & Horak, 2009; Kanekar & Aruin, 2014b; Rogers, Kukulka, & Soderberg, 1992; Slijper, Latash, Rao, & Aruin, 2002; Sousa, Silva, & Santos, 2015; Woollacott & Manchester, 1993).

Studies have reported that impaired APA generation is associated with larger compensatory muscle responses, which is often challenging for older adults and neurologically impaired people (Garland et al., 1997; Horak et al., 1984; Kanekar & Aruin, 2014a, 2014b; Slijper et al., 2002). Moreover, evidence suggests that individuals who show impairment in APAs have a greater likelihood of falls (Horak, 2006; Hyodo et al., 2012; Uemura, Yamada, Nagai, & Ichihashi, 2011). Also, individuals who have experienced falls or have fear of falling show altered APAs (Adkin, Frank, Carpenter, & Peysar, 2002; Uemura et al., 2012). This suggests that it is useful to investigate the control of APAs in order to establish tools for assessing and modifying the risk of falling. The investigation is especially important given that previous research suggests that improving APAs leads to better balance, mobility, independence, and quality of life among people with a balance deficit (Aruin, 2016; Aruin et al., 2015; Kanekar & Aruin, 2014a, 2014b, 2015; Kubicki, Mourey, & Bonnetblanc, 2015; Saito, Yamanaka, Kasahara, & Fukushima, 2014).

Although enhancing APAs has been shown to improve postural control among older adults and people post-stroke (Aruin et al., 2015; Kanekar & Aruin, 2014a, 2014b; Slijper et al., 2002; Sousa et al., 2015), studies that investigated methods for improving APAs are limited (Aruin, 2016; Geurts et al., 2005; Mansfield, Peters, Liu, & Maki, 2010; Shapiro & Melzer, 2010). Furthermore, researchers have suggested the use of APAs as a method to evaluate the recovery of patients with neurological disorders as well as detect the early signs of neurological diseases (Mancini, Zampieri, Carlson-Kuhta, Chiari, & Horak, 2009; Martinez-Mendez, Sekine, & Tamura, 2011; Slijper et al., 2002). Therefore, the investigation of tools to assess and improve APAs is warranted.

1.3.1.2. Anticipatory Postural Adjustments During Stepping Tasks. When performing a forward stepping movement, APAs are coordinated in order to prepare the body to move forward. The stepping movement is primed by a preparatory “loading–unloading” phase. This loading–unloading phase occurs when the tibialis anterior (dorsiflexor muscle) is activated while the gastrocnemius and soleus (plantarflexor muscles) are deactivated on both legs (i.e., stance and stepping legs) (Crenna & Frigo, 1991; Elble, Moody, Leffler, & Sinha, 1994; Lepers & Breniere, 1995). These muscle activation patterns result in simultaneous loading of the stepping leg and unloading of the stance leg. Further, these muscular activity changes occur in order to enable the center of pressure (COP) to move laterally and posteriorly towards the stepping foot and the COM moves slightly forward and laterally toward the stance limb to remain within the BOS. After the loading–unloading phase, the COM moves laterally towards the stance leg and forward by activating the plantarflexor muscles of the stepping leg, while at the same time deactivating the dorsiflexor muscles in both the stance and stepping legs. Lastly, the tibialis anterior on the stepping leg and the soleus on the stance leg are activated as the stepping foot lifts off the ground and the COM is propelled forward, resulting in a step (Crenna & Frigo, 1991; Elble et al., 1994; Lepers & Breniere, 1995).

As mentioned above in the previous section, older adults and people post-stroke show impairments in APAs (Kanekar & Aruin, 2014b; Sousa et al., 2015). Older adults during stepping tasks show smaller APA muscular activity in the tibialis anterior and soleus muscles compared to young adults. Further, older adults show a delayed onset of APA activity compared to young adults. For COP displacement, older adults show smaller displacement patterns compared to young adults (Kanekar & Aruin, 2014b). People post-stroke during gait initiation also show impairments in APAs compared to healthy non-disabled individuals (Sousa et al., 2015). People post-stroke show only half of the tibialis anterior relative magnitude (in paretic lower limb) compared to healthy non-disabled individuals. Further, people post-stroke show decreased soleus deactivation period and onset timing of APAs in both lower limbs (paretic and non-paretic). Lastly, people post-stroke show a decreased COP displacement backward and toward the swing limb (Sousa et al., 2015). The aforementioned information indicates that older adults and people post-stroke show impairments in APAs in both lower limbs during stepping tasks.

1.3.2. Theories, Models, Laws and Frameworks

A theory may be defined as a set of analytical principles or statements designed to structure our observation, understanding and explanation of the world (Nilsen, 2015). Theories generally involve a set of defined variables that have a unique relationship and specific predictions (Nilsen, 2015). A theory can be considered good if it provides a clear explanation of why and how specific relationships lead to specific events (Nilsen, 2015). Theories can be classified according to their abstraction, with high abstraction level theories (i.e., general or grand theories) having a grand scope, middle abstraction theories explaining limited sets of phenomena and lower abstraction theories being empirical generalization of limited scope and application (Nilsen, 2015).

Models are closely related to theories, and are usually described as theories with a more narrow scope of explanation (Nilsen, 2015). Models are generally descriptive; whereas theories are descriptive and explanatory (Nilsen, 2015). The overall purpose of models is to illustrate a phenomenon or a specific part of a phenomenon (Nilsen, 2015). A term that is closely related to models is laws (Powers & Knapp, 2011). Laws are a concise form of description, usually in the form of a mathematical equation, used to describe a pattern in nature (Powers & Knapp, 2011). Laws are highly generalizable and relatively certain and they are concerned with describing and predicting a phenomenon (Powers & Knapp, 2011).

A framework usually represents a structure, overview or outline that consists of various descriptive categories, such as concepts, constructs or variables, and the relations between them are assumed to describe a phenomenon (Nilsen, 2015). Similar to models, frameworks do not provide explanations; they only describe empirical phenomena by fitting them into a set of categories. A framework, while useful for contextualizing, is not typically falsifiable, whereas a theory is falsifiable (Nilsen, 2015).

It is important that healthcare research is guided by theory (Alderson, 1998; Brazil, Ozer, Cloutier, Levine, & Stryer, 2005). The use of theory provides a systematic view of a phenomenon as it aims to explain or predict the relations among variables (Alderson, 1998; Brazil et al., 2005). Theory-driven work offers many advantages to the researchers such as: (i) it helps identify appropriate study questions and target groups; (ii) clarify methods and measurement issues; (iii) provide more detailed and informative descriptions on characteristics of the intervention and supportive implementation conditions; (iv) detect unintended effects; (v) assist in analysis and interpretation of results; and, (vi) the successful application of an intervention to different settings (Brazil et al., 2005). Theory is also advantageous for healthcare-research stakeholders as it provides explanations about how an intervention or an approach works and whether it will work in a given environment (Brazil et al., 2005). Moreover, the use of theory facilitates the implementation of an approach or intervention to different settings (Brazil et al., 2005).

1.3.3. Fitts' Law

Fitts' law states that movement time (MT) changes according to the movement amplitude (A) and target width (W). A formal linear relationship is represented by $MT=a+b \log_2 (2A/W)$, where MT is movement time, a and b are empirical constants, A and W are amplitude of movement and width of target, respectively (Fitts, 1954; Fitts & Peterson, 1964). The logarithmic function of this formula is called the index of difficulty (ID), ID= $\log_2$ (2A/W), and it is measured in bits (Fitts, 1954; Fitts & Peterson, 1964). In other words, Fitts' law can be described as a relationship between MT and task difficulty, when aiming for a target, MT increases with task difficulty.

Paul Fitts discovered this law after conducting three experiments for his 1954 paper (Fitts, 1954). The first experiment (Fitts, 1954) involved participants performing a reciprocal tapping task on a plate that had two targets. The size of targets and distance between them were varied to control the difficulty of the task, with four different target widths (i.e., Fitts' law Ws) and four different distances between targets (i.e., Fitts' As). This resulted in 16 different combinations or IDs. A counter was used to determine the number of successful taps and a timer was used to determine the time for each trial. Trials lasted 15 seconds and were followed by 55 seconds rest. Sixteen participants were asked to hold a stylus to perform the task and place their hand midway between plates. The assessor gave participants the following instruction for the task:

> Strike these two target plates alternately. Score as many as you can. If you hit either of the side plates an error will be recorded. You will be given a 2-second warning before a trial. Place your hand here and start tapping as soon as you hear the buzzer. *Emphasize accuracy rather than speed*. At the end of each trial I shall tell you if you have made any errors. (p.384)

Participants were tested in all 16 conditions with a different random sequence used for each subject. The second experiment (Fitts, 1954) involved transferring plastic washers from one pin to the other. Similar to the first experiment, the width of target and amplitude of movement were changed to control difficulty. Four different distances (As) between pins, and four different disc sizes (Ws) were used for the experiment; yielding 16 different IDs. Sixteen participants were recruited for this experiment and similar to the first test, the trials were performed in a random order. The third experiment (Fitts, 1954) involved transferring small pins from one set of holes to another. In this task four sizes of pins (Ws) were used to perform five different amplitudes (As) of movement; yielding 20 different conditions (IDs). Similar to the above, sequence of condition was randomized and a timer was used to record the performance times for the twenty participants of this experiment. The major finding of the aforementioned experiments is that there was a relationship between MT and task difficulty. When performing goal-directed movements, MT increases with task difficulty, which can be controlled by the width (W) and amplitude of movement (A) (i.e., ID).

1.3.3.1. Older adults in Fitts' task paradigms. Several studies have shown the robustness of Fitts' law and that it holds true in several contexts (Plamondon & Alimi, 1997). Fitts' law has been shown to apply during different movement types (e.g., serial, discrete, rotatory). It was also found to apply among different populations (children, young adults, elderly) and across limbs and body parts (upper and lower extremity, eye movements) (Plamondon & Alimi, 1997). The applications (and variations) of Fitts' law extend to the area of computer sciences (Bootsma, Fernandez, & Mottet, 2004). For example, computer user interfaces rely on simple aiming movements (i.e., pointing mouse cursor to window or icon), and this mode of input (pointing of mouse cursor) makes interaction with computers more natural (Bootsma et al., 2004).

Studies that have used a Fitts' task paradigm among older adults have reported significant differences in their results when comparing older to younger adults (Passmore, Burke, & Lyons, 2007; Sleimen-Malkoun, Temprado, & Berton, 2013). A study by Passmore et al., (2007), compared eight older adults to eight younger adults performing discrete head aiming movements. The head movements controlled a mouse cursor on a monitor in front of participants. The task was to control a program that is running a Generalized Fitts' Law Model Builder. The Fitts' task involved 3 different movement amplitudes and 3 different target sizes, which yielded 9 different IDs ranging from 3.15-6.23 bits. The results of the study showed that Fitts' law holds during head aiming movements for younger and older adults. However, older adults had longer MTs than younger adults at each ID. Further, the increases in MT with age were disproportionately greater at higher IDs. Another observation from this study was that standard deviation (SD) of MT was greater for older adults than younger adults. Furthermore, the authors found that ID affected the performance of older adults more than younger adults (Passmore et al., 2007). In another study by Sleimen-Malkoun et al., (2013) the authors recruited 10 young adults and 14 older adults. Participants performed a typical Fitts' task that involve pointing with the upper extremity with an ID ranging from three to seven bits. The results showed that older adults were slower than younger adults. The authors indicated that their results support the general slowing hypothesis (GSH). Further, they argue the GSH is not only specific to the cognitive domain, but it even extends to the motor domain as seen in their results. In summary, a number of studies show that although Fitts' law holds among older adults, they show a general pattern of slower performance compared to younger adults and are more affected by the increase in difficulty.

1.3.3.2. People post-stroke in Fitts' task paradigms. A few studies have used Fitts' law to investigate the motor control of goal-directed movements among individuals post-stroke (McCrea & Eng, 2005; Winstein & Pohl, 1995; Zimmerli et al., 2012). In a study by Winstein and Pohl (1995) the authors investigated the effects of unilateral brain damage due to CVA on the control of goal-directed hand movements. Thirty right-hand-dominant participants were recruited for this study; among the participants, 20 were unilateral stroke patients and 10 were aged-matched non-disabled controls. Of the 20 participants post-stroke, ten participants had left-sided hemiparesis and ten had right-sided hemiparesis. Participants were required to perform three separate tasks. The first task was to repeatedly tap a single 8-cm wide target using a stylus for the duration of 10 seconds. The second task involved tapping alternately between two 8-cm wide targets that were 37 cm apart for the duration of 10 seconds. The last task was to tap alternately two 2-cm wide targets that were 37 cm apart for the duration of 10 seconds. The previous tasks represented low, medium and hard IDs, respectively. Each task was performed three times. Control participants performed the three tasks once with the left hand and then repeated the three tasks with the right hand. Participants post-stroke performed the tasks with the non-paretic hand. The outcome measures in the study were number of taps, movement time (MT) and kinematic measures of movement. The results of the study showed participants' performances were consistent with Fitts' law as average MTs increased with increases in IDs. However, participants post-stroke showed an increased MT in comparison to controls. This finding suggests that what was commonly termed the 'unaffected side' does in fact show subtle deficits, and rehabilitation efforts should also address the impairments of the 'less-affected side'. An interesting finding in the study was that the increase in MT with higher IDs was disproportionately higher when comparing people post-stroke to controls. Also, the SDs of MTs were higher for people post-stroke compared to controls (Winstein & Pohl, 1995).

In a study by McCrea and Eng (2005), twenty individuals post-stroke and ten age-matched non-disabled controls were recruited. The study aimed to investigate the effect of target size and distance on reaching tasks in three different arm conditions: more and less affected arms in persons with stroke and the non-dominant arm of controls. The reaching movement in this study followed a Fitts' paradigm with three target distances and four target widths. The outcome measures included MTs of participants, kinematic analysis of movements and Fitts' slope and intercept. The results showed that Fitts' slope and intercept were increased in the more affected arm of participants post-stroke and were significantly correlated with measures of muscle tone (modified Ashworth scale [MAS]) and measures of motor impairment (Fugl-Meyer scale). Moreover, the authors reported that for both arms of participants post-stroke, Fitts' slope and intercept were increased and correlated to more indirect, segmented, and positively skewed movement as determined by kinematic measures of path accuracy, trajectory corrections and planning strategy, respectively. The authors concluded that people post-stroke show significant deviations from straight-line, goal-directed movements compared to healthy non-disabled adults, which indicate limitations in motor planning and execution (McCrea & Eng, 2005).

Fitts' law has also been shown to be useful for controlling the difficulty of rehabilitation programs. In a study by Zimmerli et al. (2012), the authors recruited ten people post-stroke to undergo an upper extremity exercise program. Participants used a weight compensation system called the Armeo® Spring. This orthotic system counterbalances the patient's paretic arm against gravity using its integrated springs, which enhances any residual functions of the patient thus enabling the training of active reaching movements. The authors attached electronic sensors to this device in order to control an augmented feedback application. The augmented feedback application involve reaching tasks that utilize Fitts' law and divided into three difficulty conditions (easy, medium and hard) based on IDs. Participants performed the exercises twice, once with the less affected arm and once with the more affected arm. The results of the study showed that the mechanism was capable of balancing the difficulty of an exercise to help participants achieve successful scores. Also, the results showed that the three conditions significantly differed from each other for both arms (Zimmerli et al., 2012).

In summary, the previous studies show that people post-stroke show significant differences when performing Fitts' tasks compared to non-disabled individuals due to impairments in motor planning and execution. These differences in motor performance can be observed on both sides, with a marked impairment in the more affected side.

1.3.4. Focus of Attention

The focus of attention concept postulates that when performing a motor task, it is better to direct attention towards the effects that the movement has on the environment (external focus of attention) than directing attention on the movement itself (internal focus of attention) (Wulf et al., 1998). For example, if an individual attempts to balance on a stabilometer (i.e., maintain the stabilometer's platform in a horizontal position), an instruction for an external focus of attention would be to ask the individual to maintain the lines of the platform in a horizontal position. On the other hand, an instruction to promote an internal focus of attention would be to ask the individual to maintain feet in a horizontal position. In a review by Wulf (2013), the author iterates numerous studies that show the benefits of an external focus of attention for different motor tasks and different populations (e.g., non-disabled young and older adults and people with neurological impairments) (Wulf, 2013).

Studies that have investigated the beneficial effects of adopting an external focus of attention may be viewed as either relating to movement effectiveness or movement efficiency (examples are elaborated below). Another view of focus of attention studies is related to how the investigators manipulated the participants' attentional focus. In some studies the investigators used instructions, while other studies used feedback when comparing different attentional foci.

Lastly, a number of studies aimed to discern whether the effects seen when utilizing different attentional foci are related only to performance or if adopting an external focus can promote learning of motor skills. In the following sections I will elaborate on the beneficial effects of adopting an external focus of attention.

1.3.4.1. Movement effectiveness. A number of studies have looked at movement effectiveness (e.g., balance or accuracy) during different attentional foci (Wulf, 2013). In the original paper that proposed focus of attention as an approach to manipulate performance, Wulf et al. (1998) recruited 33 participants who were required to perform ski-type slalom movements on a ski-simulator. Participants were randomly assigned to one of three groups: an internal focus group, an external focus group or a control group. The participants were instructed that the task was to move with as large amplitude as possible. Additional instructions were given to the internal focus group and told to 'try to exert force on the foot'. The external focus group was instructed to 'try to exert force on the platform of the ski-simulator'. The control group did not receive any additional instructions. Participants performed a total of 22 trials, each trial lasting 90 seconds during the course of 3 consecutive days. The main dependent variable was movement amplitude. Results showed that all groups improved in movement amplitude over the course of the 3 days. However, the external focus group showed significantly larger movement amplitudes compared to the other groups (Wulf et al., 1998).

In a more recent study thirty-two healthy, older adults were recruited for an experiment that involved maintaining balance on a stabilometer (Chiviacowsky, Wulf, & Wally, 2010). Participants were divided into two groups, an internal focus and an external focus. The external focus group was instructed to concentrate on keeping markers on the stabilometer horizontal, while the internal focus group was instructed to concentrate on keeping their feet horizontal.

Participants trained for 10 trials (each 30 seconds) and then performed a retention test (five, 30 seconds trials) one day later. The dependent variable was time maintaining balance, and the results showed that the external focus group had longer performance times in maintaining balance than the internal focus group (Chiviacowsky et al., 2010).

Other studies related to focus of attention aimed to investigate the benefit of adopting an external focus among patients with neurological impairments. In a study that involved 14 participants diagnosed with idiopathic Parkinson's disease, the authors compared postural instability during three conditions, an internal focus of attention, an external focus of attention or control (Wulf, Landers, Lewthwaite, & Tollner, 2009). Participants were asked to stand and maintain standing balance on an unstable surface (inflated rubber disk). The rubber disk was placed on a force plate system and in counterbalanced orders, participants were instructed to reduce the movement of their feet (internal focus) or reduce movement of the rubber disk (external focus), or they were not given attentional focus instructions (control). Postural sway of participants was assessed by measuring the root-mean-square error (RMSE) of the center of pressure (COP). Results showed that the external focus condition led to the least amount of postural sway among participants. Further, there were no significant differences between control and internal focus conditions (Wulf et al., 2009).

In a study that used accuracy as an outcome of motor skills, the investigators recruited 67 people who were novices in dart throwing (Marchant, Clough, & Crawshaw, 2007). Subsequently, participants were randomly allocated to either: control, internal focus or external focus groups. The objective was to throw darts on a target that consisted of 10 black concentric circles: the center circle was 10 cm in diameter, and each successive circle was 10 cm larger in diameter. Circles were numbered 0 – 9, with a zero score being a perfect shot in the center circle of the target. The internal focus group was instructed to focus on their movement, while the external focus group was instructed to focus on the outcome of their movement. The control group was not given any specific instruction. All participants had 10 practice throws, followed by 40 test throws. The dependent variable was the score achieved on the target for each throw. Data analysis revealed that participants who were in the external focus condition performed significantly better than the other two groups (Marchant et al., 2007).

1.3.4.2. Movement efficiency. Numerous studies have looked at movement efficiency (e.g., muscle activity, force production or movement kinematics) while utilizing different attentional foci (Wulf, 2013). In a study that assessed movement speed and muscular activity (using electromyography [EMG]), the authors found that an external focus of attention yields faster movements and more efficient muscle activation (Vance, Wulf, Tollner, McNevin, & Mercer, 2004). Vance et al. (2004) reported that participants who performed biceps curls under an external focus instruction (focusing on curl bar) had faster movement speeds compared to an internal focus group (focusing on arm). Furthermore, the authors reported that when measuring EMG for both agonist and antagonist muscle groups, the external focus condition led to significantly reduced EMG activity (Vance et al., 2004). The previous findings were corroborated by a more recent study that involved participants performing the same task (biceps curls) under three conditions: external focus, internal focus and control (Marchant, Greig, & Scott, 2008). The results showed that an external focus condition was associated with reduced EMG activity not only compared to an internal focus group but also compared to a control group. Additionally, the same research group repeated the experiment but also measured force production using an isokinetic dynamometer (Marchant, Greig, & Scott, 2009). Results showed that an external focus not only produces less EMG activity but also greater maximal forces compared to an internal focus. These studies suggest that an external focus of attention promotes the efficiency of movements.

In a recent study a group of researchers investigated both kinematics and EMG activity of the upper extremity during dart throwing (Lohse, Sherwood, & Healy, 2010). Two groups were recruited, with one instructed to focus on the flight of the dart (external focus) and the other group instructed to focus on their arm (internal focus). Analysis of kinematic data showed that external focus group had increased variability in the shoulder angle at the moment of release of dart compared to the internal focus group. This variability observed among participants with external focus is similar to 'functional variability' that is seen among expert performers (Muller & Loosch, 1999). Another finding in the study by Lohse et al. (2010) was that the external focus group had reduced EMG activity at triceps brachii muscle compared to internal focus group. The authors also found that accuracy of dart throwing among external focus group was superior to internal focus group. The authors concluded that their results give support that adopting an external focus attention leads to better movement efficiency as seen in the superior accuracy performance and more efficient EMG activity (Lohse et al., 2010).

1.3.4.3. Using feedback to manipulate focus of attention. The aforementioned studies primarily used verbal instructions in order to control for the two different types of attentional foci. However, feedback can also be used to manipulate different attentional foci. In a study by Shea and Wulf (1999), thirty-two participants were recruited to maintain balance on a stabilometer. Participants were randomly assigned to one of four groups: (1) internal focus using feedback, (2) external focus using feedback, (3) internal focus using instruction; and, (4) external focus using instruction. Feedback was in the form of a computer monitor shown to participants concurrently with their performance. The monitor showed two horizontal lines on the left and right sides of the screen that represented the actual position of the platform of the stabilometer used in the study. The internal focus group was instructed to think of the moving lines as representing their feet, while the external focus group was instructed to think of the two lines as the stabilometer platform. The two other groups that received instructions were told to either try to keep their feet horizontal (internal focus), or try to keep the platform horizontal (external focus). The procedure involved participants trying to balance the stabilometer as long as possible during 90-seconds trials. All participants performed 7 practice trials on each of two days of practice under their specific conditions. On the third consecutive day, a retention test was conducted that involved 7 trials without feedback or instructions. The main dependent variable was RMSE with the 0° position of the platform as criterion. Results of the retention test showed that the two groups that received feedback were more effective than the no-feedback groups; with the external focus feedback group performing better than the internal focus feedback group. Further, external focus groups had generally lower error scores than internal focus groups (Shea & Wulf, 1999).

1.3.4.4. Performance or learning effect? Focus of attention studies have used delayed retention tests (without instructions or reminders) in order to investigate if there is a learning effect associated with using different attentional foci. The delayed retention tests may give an indication as to whether the effects of different attentional foci are due to temporary performance or a permanent learning effect. However, a weakness in this approach is that participants may still continue to use their respective focus of attention during retention tests even without instructions or reminders. In order to address this issue, a study was conducted that used a retention test that limits the participants from adopting their respective focus of attention from the acquisition phase (Totsika & Wulf, 2003). Totsika and Wulf (2003) recruited 22 subjects for a balance task study. All participants received training on the balance task with either an external or internal foci of attention. A retention test was conducted one day later for all participants. The retention test involved performing the primary task (balance task) in addition to an attention-demanding secondary task, which was counting back in threes. Results showed that the external focus group performed better in the balance task compared to the internal focus group, suggesting that there was a learning effect (Totsika & Wulf, 2003).

Another indication that an external focus of attention promotes learning are studies of different foci of attention during supra-postural tasks (Wulf, Mercer, McNevin, & Guadagnoli, 2004; Wulf, Weigelt, Poulter, & McNevin, 2003). Supra-postural tasks are tasks that have a postural component (balance) and another motor component. An example of a supra-postural task is holding a pole or juggling (motor component) while standing or walking (postural component). In a study by Wulf et al. (2004), participants were asked to stand on a compliant surface (rubber inflated disk) that was on a force plate system, while holding a 2-meter pole horizontally. A uniaxial accelerometer was mounted on the pole to record vertical sway of the pole. Participants were asked to stand as still as possible and were instructed to either focus on the pole (external focus) or their hands (internal focus). The overall results showed that when participants adopted an external focus they had less postural sway and better pole stability.

The aforementioned study by Wulf and colleagues (2004) used a within-participants design (i.e., participants performed under both foci of attention conditions). Therefore, the study addressed immediate effects of focus of attention on performance but not on learning. In another study by Wulf and colleagues (2003), the authors recruited 18 subjects for a study that involved participants balancing on a stabilometer while holding a wooden tube (length 41.5 cm) horizontally. Participants were assigned to either an internal focus group or an external focus group. The focus of attention instruction was related to the supra-postural task, either focus on the keeping hands horizontal (internal focus) or focus on keeping the tube horizontal (external focus). Subjects received 2 days of training. A transfer test was conducted on the third day, which involved the investigators removing the supra-postural task that was present during training and used for the focus of attention instructions. Thus, any change in performance of participants on the balance task would be attributed to a learning effect as the supra-postural task (i.e., task used for focus of attention) was eliminated. Results of the transfer test showed that participants who trained with an external focus had better balance performance on stabilometer compared participants who trained with an internal focus. These results were found even with the removal of the source of focus of attention (supra-postural task) (Wulf et al., 2003).

In addition to the learning effect promoted by adopting an external focus, some research suggests that adopting an external focus has a potent effect. In a study by Lohse and Sherwood (2011), subjects were recruited and divided into 3 groups, external and internal foci, and control. The study's task was an isometric force production task and the main dependent variable was time to failure of task. Participants in the internal and external foci groups were biased to believe that their respective focus of attention is better than the other. This was done by presenting data of a previous study by the same research group and stating that the superior performance was seen due to the focus of attention they will adopt. Results showed that the external focus group had better performance (Lohse & Sherwood, 2011). Similar results were also seen when participants were trained on the two forms of foci of attention and then given the option to choose one of the two types of attention. The results showed that participants who choose an external focus outperformed those who choose an internal focus (Marchant, Clough, Crawshaw, & Levy, 2009). In conclusion, the findings of these studies provide evidence that an external focus of attention leads to better performance during motor tasks. Further, there appears to be a learning effect as seen in the results of the above mentioned studies.

1.3.5. Challenge Point Framework

The CPF put forward by Guadagnoli and Lee (2004) provides context for understanding the different effects of various practice conditions during the learning of a motor skill (Guadagnoli & Lee, 2004). The CPF relates practice variables to (i) the skill level of the learner, (ii) the difficulty of the motor task and (iii) the information related to the motor skill. The skill level of the learner is related to whether an individual is an expert or a novice in a particular motor skill. Task difficulty is classified according to its 'nominal' and 'functional' difficulty. Nominal task difficulty includes only the characteristics of the task, regardless of who is performing the task and under what conditions. Functional task difficulty refers to the challenge of the task, taking into consideration the skill level of the person performing the task and the conditions under which it is performed. The third aspect of the CPF illustrates that the information related to the motor skill is derived from the nature of the task and the associated feedback the person may be provided. The CPF states that learning is influenced by the information available during performance in addition to the learner's ability to use this information. Guadagnoli and Lee (2004) state that as the difficulty of a motor task increases, the overall performance decreases depending on the ability of the performer. However, the authors suggest that in order to achieve maximum learning of a motor skill, there is an "optimal challenge point" in the degree of task difficulty and availability of information, which leads to optimal learning of motor skills. At this optimal challenge point the learner is being ideally challenged with the task difficulty relative to their skill level, and then efficient learning of a motor skill can occur (Guadagnoli & Lee, 2004).

A number of studies have utilized the CPF in clinical research and found that the CPF is useful for designing therapeutic programs (Miller, Hunt, Pollock, Bryant, & Garland, 2014; Perry, Zeleznik, & Breisinger, 2014; Pollock, Boyd, Hunt, & Garland, 2014). In a case series study by Pollock et al. (2014), the authors used the CPF to help design a therapeutic program for retraining people post-stroke in multidirectional stepping reactions to improve community-level walking balance. Four community-dwelling participants in the chronic stage of stroke recovery were recruited. All participants were able to independently ambulate. The intervention used involved participants performing self-initiated stepping reactions by standing straight and leaning, pivoting from ankles in 4 directions: forward, backward, left and right. Participants were asked to let themselves fall until they felt they had to step to prevent falling. The therapeutic program was conducted 3 times/week for 4 weeks. Testing was done pre-intervention, 2 weeks into the program and at the end of the program. In addition, testing was also done 1 year following the end of the therapeutic program. In order to follow the CPF model, progression of task difficulty was controlled in the following manner: At first, training was in blocked practice of direction and stepping feet and then progressed to random order. Physical assistance progressed from a safety harness, to a walking belt, to the experimenter spotting the participants' performance. In regard to feedback, the therapists provided feedback to the participants about all aspects of stepping reaction combined with knowledge of the results to enhance motor learning. Feedback was faded by the therapists as participants progressed through practice. Walking balance was assessed using the community balance and mobility scale (CB&M). In addition, kinematic data were collected from participants, which involved using reflective markers and a motion camera to determine step length and average step velocity. The results of the study showed that participants after training improved in walking balance as measured using the

CB&M scale. These improvements were still present 1 year later. Also, movement kinematics showed significant improvement during the course of the intervention with less retention after one year compared to CB&M retention. The authors concluded that CPF application in retraining of stepping reactions to improve community-level walking balance in people with chronic stroke appears to be promising. Further, the CPF provides a good theoretical framework for progression of functional task training in the field of neuro-rehabilitation (Pollock et al., 2014).

In another study by Perry et al. (2014), the authors wanted to implement a behavioral change in clinical practice among neurologic physical therapists. In this study the authors wanted to conduct a knowledge translation activity in their local rehabilitation setting as they wanted to encourage the use of a novel (evidence-supported) method for gait training among patients with hemiparesis (Perry et al., 2014). This novel program, which is called non-supported gait training, used the CPF as a guideline for controlling its intensity. The overall results of the study indicate that patients following the novel therapeutic program, which was guided by the CPF, show an improvement in their gait compared to their pre-treatment results (Perry et al., 2014). Miller et al. (2014) published a protocol for a randomized controlled trial (RCT) to compare a novel form of balance rehabilitation, which uses the CPF, to conventional balance therapy for people post-stroke. In this study, Miller et al. (2014) details this novel program and how the use of the CPF is beneficial for retraining balance control for people post-stroke. At the end the authors indicate that this program may be useful for retraining walking balance in an outpatient population following stroke and that the program has been deliberately developed to optimize its generalizability for outpatient stroke clinical settings. In summary, the previous studies suggest that the CPF can be beneficial for designing therapeutic programs. Further, it provides the contextual basis on how the difficulty of a motor task and the skill level of the performer affect learning of a motor skill.

The literature review above suggests that motor behavior concepts can be utilized in clinical practice. Fitts' law can be used to control the difficulty of motor tasks. Further, Fitts' law tasks can distinguish between the motor performances of different populations (e.g., older adults vs. young adults). Focus of attention studies indicate that an external focus of attention yields better performance during motor tasks. The CPF is beneficial for the learning of motor skills as it provides a theoretical framework to relate the skill level of the learner to the difficulty of the motor task and the information related to the motor skill. Moreover, the aforementioned motor behavior concepts have been used in multiple studies related to balance control. However, there is no previous knowledge synthesis or review study related to these motor behavior concepts that follows a well-established guideline to review Fitts law, focus of attention or CPF. Utilizing specific guidelines to conduct such a review will identify all relevant literature related to the topic. A knowledge synthesis of studies that used these motor behavior concepts during balance control tasks would provide a comprehensive look at the existing literature. Further, a review examining these motor behavior concepts would solidify the usefulness of these concepts in balance control studies. The results of this review would be helpful for clinicians and researchers in the fields of motor behavior and rehabilitation.

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CHAPTER 2: MOTOR BEHAVIOR CONCEPTS IN THE STUDY OF BALANCE: A SCOPING REVIEW

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Contributions of Authors to the Manuscript

The idea to conduct this review was made after a discussion with my advisor Dr. Passmore. I have performed the bulk of writing the protocol, conducting the literature search, reviewing the papers and writing the manuscript. With the aid of my committee, especially Dr. Sibley, the research questions and procedures for the methodology of this scoping review were refined in order to generate this study. Working in collaboration with my colleague Dr. Geoffrey Gelley and under the supervision of Dr. Passmore, the search results were screened for eligibility and then the relevant data needed from the included studies were extracted to write the manuscript. The initial findings of this scoping review were presented in poster form at the Canadian Society for Psychomotor Learning and Sport Psychology Conference held in St. John's, October 2017. I wrote the manuscript for the study and subsequently shared it with the co-authors. All authors critically revised the manuscript for intellectual content and approved the final draft for submission. I have prepared the manuscript and it was submitted for publication to the *Journal of Motor Behavior*. A revised version has been accepted for publication in this journal.

Preface

There is a lack of a knowledge synthesis of the use of motor behaviour concepts in balance control studies. Further, no previous study has examined specific concepts related to motor behaviour and discussed their relevance to clinical practice. Based on the literature review above, multiple studies related to Fitts' law, focus of attention and CPF have used these concepts in balance control studies. Therefore, we conducted this scoping review to examine the use of Fitts' law, focus of attention and the challenge point framework among studies related to balance control. The results of this review provide a comprehensive look at the existing evidence. Further, we identify important knowledge gaps for future research in order to provide recommendations for implementing the best available evidence in clinical practice.

Throughout this manuscript we discuss studies related to the scope of this review. Subsequently, we examine the findings of these studies and the usefulness of the selected motor behaviour concepts for balance control studies. We identify key findings and provide important recommendations for future research. The results of this review provide important information for clinicians who are involved in balance training and for researchers in the fields of motor control and learning and rehabilitation.

Lastly, the findings of this review helped inform our two subsequent studies. In this review we identified all studies related to anticipatory postural adjustments that have utilized the selected motor behaviour concepts. Moreover, this scoping review highlighted the advantages of utilizing Fitts' law for balance tasks; and the benefits adopting an external focus of attention. Further, the results provided context for the two subsequent studies and provided us with the theoretical basis related to the selected motor behaviour concepts. A revised version of the following manuscript has been accepted for publication in the *Journal of Motor Behavior*.

Abstract

Previous research suggests that using Fitts' law; attentional focus or challenge point framework (CPF) is beneficial in balance control studies. A scoping review was conducted to examine studies that utilized these motor behavior concepts during balance control tasks. Questions for this review were: (1) Have motor behavior concepts, specifically Fitts' Law, focus of attention and CPF, been used for clinical studies related to balance control among adults? (2) What are the findings of studies that have used these selected motor behavior concepts? An extensive literature search that involved 4 databases (PubMed, CINAHL, Scopus and Web of Science) was performed up to January 2018. Following the literature search, a study selection process was done to include studies that have utilized one (or more) of the selected motor behavior concepts in a study involving standing balance. Two independent reviewers performed the study selection, which was then followed by data extraction of the search results. Forty-six studies were identified, with 2 studies related to CPF, 12 studies related to Fitts' law and 32 studies related to focus of attention. The CPF appears to be a useful method for designing a progressive therapeutic program. Fitts' law can be used as a tool for controlling the difficulty of motor tasks. Focus of attention studies indicate that adopting an external focus of attention improves task performance. Overall, studies included in this review report benefit when using the selected motor behavior concepts. However, the majority (>80%) of studies included in the present review involved healthy populations, with only 3 clinical trials. In order to ascertain the benefits of the selected motor behavior concepts in clinical settings, future research should focus on using these concepts for clinical trials to examine balance control among people with balance impairments.

2.1. Introduction

An essential component in standing is balance control. Balance control, defined as the ability to keep the center of mass within the base of support (Shumway-Cook & Woollacott, 2012), enables individuals to adopt various postures, react to external perturbations, and use anticipatory postural adjustments that precede voluntary movements (Marsh & Geel, 2000; Orrell, Eves, & Masters, 2006; Walker, Brouwer, & Culham, 2000; Woollacott & Shumway-Cook, 2002; Zech et al., 2010). It is important to examine balance and its underlying mechanisms in order to develop new rehabilitation techniques, improve therapeutic outcomes, and decrease the incidence of falls (Chang et al., 2004; Muir, Berg, Chesworth, Klar, & Speechley, 2010; Sherrington et al., 2008).

The field of motor behavior offers knowledge that can be utilized for assessing balance control and postural adjustments. The field of motor behavior has already influenced clinical practice to some extent (Magill & Anderson, 2014; Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012). For example, the introduction of the motor program theory has led rehabilitation clinicians to move beyond a reflex as an explanation for disordered motor control (Henry & Rogers, 1960; Klapp, 2010; Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012). Additionally, the contextual interference concept has become a common approach within motor skill training settings (e.g., rehabilitation settings) (Brady, 2008; Shea & Morgan, 1979; Shumway-Cook & Woollacott, 2012).

In addition to motor behavior theories, there are three concepts of motor behavior that are also utilized in clinical practice (Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012), which are Fitts' law, focus of attention and the challenge point framework (CPF) (Fitts, 1954; Fitts & Peterson, 1964; Guadagnoli & Lee, 2004; Wulf, Höß, & Prinz, 1998). These motor behavior concepts represent seminal landmarks in the field of motor behavior (Schmidt & Lee, 2011; Shumway-Cook & Woollacott, 2012). Fitts' law describes the relationship between speed and accuracy and states that movement time (MT) changes according to the movement amplitude (A) and target width (W). A formal linear relationship is represented by $MT=a+b \log_2 (2A/W)$, where MT is movement time, a and b are empirical constants, A and W are amplitude of movement and width of target, respectively (Fitts, 1954; Fitts & Peterson, 1964). Put simply, Fitts' law indicates that it will take longer to move to a small target than to a large target for a given distance. Similarly, for a given target size, it will take longer to move a longer amplitude than a shorter amplitude. Another concept in motor behavior is focus of attention, which postulates that when performing a motor task it is better to direct attention towards the effects of an action on the environment (external focus of attention) than to direct attention to the specific movements needed to produce the action (internal focus of attention) (Wulf et al., 1998). Finally, CPF provides context for understanding the different effects of various practice conditions during the learning of a motor skill (Guadagnoli & Lee, 2004). CPF relates practice variables to (i) the skill level of the learner, (ii) the difficulty of the motor task, and (iii) the information related to the motor skill. Guadagnoli and Lee (2004) state that as the difficulty of a motor task increases, the overall performance decreases depending on the ability of the performer. However, the authors suggest that in order to achieve maximum learning of a motor skill, there is an "optimal challenge point" in the degree of task difficulty and availability of information, which leads to optimal learning of motor skills. At this optimal challenge point the learner is being optimally challenged with the task difficulty relative to their skill level, and then efficient learning of a motor skill can occur.

Fitts' law is one of the most studied and robust laws of motor behavior as it explores the tradeoff between speed and accuracy during goal-directed movements (Fitts, 1954; Fitts & Peterson, 1964). Further, Fitts' law has been applied in a variety of contexts (Plamondon & Alimi, 1997), including clinical applications, which merits its inclusion in the present review. For example, Fitts' law's W and A can be used as parameters for controlling the difficulty of a motor task. As Fitts' law's index of difficulty (ID) increases, the difficulty of the motor task becomes more pronounced and performance is challenged. This technique of controlling difficulty via Fitts' ID was used in several clinical studies that have reported its benefit for accurately predicting performance (MT) via controlling W and A (Descarreaux, Passmore, & Cantin, 2010; McCrea & Eng, 2005; Passmore, Burke, Good, Lyons, & Dunn, 2010; Passmore et al., 2014; Passmore et al., 2015; Winstein & Pohl, 1995; Zimmerli et al., 2012). Further, as discussed in this review, several studies have investigated the changes that occur in anticipatory postural adjustments prior to movement initiation during Fitts' law tasks. The findings of these studies provide important information related to balance control.

Focus of attention is included in the present review because the early work related to this concept attempted to understand balance control and how balance can be influenced by different task instructions (Wulf et al., 1998). In a recent review of the focus of attention concept it was shown that ample evidence exists to support that the application of focus of attention for motor skill learning yields positive effects (Wulf, 2013), including balance control (Chiviacowsky, Wulf, & Wally, 2010; Jackson & Holmes, 2011; Landers, Wulf, Wallmann, & Guadagnoli, 2005; Laufer, Rotem-Lehrer, Ronen, Khayutin, & Rozenberg, 2007; McNevin, Shea, & Wulf, 2003; McNevin & Wulf, 2002; Rotem-Lehrer & Laufer, 2007; Shea & Wulf, 1999; Wulf et al., 1998; Wulf, Landers, Lewthwaite, & Tollner, 2009; Wulf & McNevin, 2003; Wulf, McNevin, &

Shea, 2001; Wulf, Mercer, McNevin, & Guadagnoli, 2004; Wulf, Shea, & Park, 2001; Wulf, Weigelt, Poulter, & McNevin, 2003). Despite the evidence suggesting that the use of focus of attention is beneficial for motor skill learning, including balance training, the uptake of focus of attention has lagged behind in clinical practice (Durham, Van Vliet, Badger, & Sackley, 2009; Johnson, Burridge, & Demain, 2013; Porter, Wu, & Partridge, 2010). As such, we have included the focus of attention concept in our review in order to provide additional support, which may in turn aid in implementing this concept into clinical practice.

The CPF is a relatively new concept in the field of motor behavior (Guadagnoli & Lee, 2004). Recent studies utilizing this framework have found a benefit when using the CPF in clinical and rehabilitation contexts (Miller, Hunt, Pollock, Bryant, & Garland, 2014; Onla-or & Winstein, 2008; Perry, Zeleznik, & Breisinger, 2014; Pollock, Boyd, Hunt, & Garland, 2014). The authors reported that using the CPF was helpful as a theoretical framework for guiding balance rehabilitation training. Given the potential relevance and benefit of the CPF and its applicability in clinical practice, we have included it in our review.

The above concepts of motor behavior are well established, and they have been used in studies related to balance control. However, the published literature lacks a knowledge synthesis that examines the use of the aforementioned motor behavior concepts in balance control studies. This review provides a comprehensive look at the existing evidence among studies related to balance control when using the selected motor behavior concepts. Further, this review identifies knowledge gaps for future research. Identifying these gaps is an important step towards implementing the best available evidence in clinical practice (Straus, Tetroe, & Graham, 2013). The results of this scoping review are useful for researchers, clinicians and knowledge users in the fields of rehabilitation and motor training. The potential impact on research that this review might have includes: clarifying and substantiating the usefulness of the selected motor behavior concepts in balance control, identifying possible knowledge gaps or research ideas to guide future studies; and, instigate a discussion between researchers in basic science and clinical research to help close the gap between basic research and clinical application (Butler, 2008). This review is also beneficial to clinicians who are involved in balance training. The results of the review may inform clinicians and knowledge users on how to best use the selected concepts of motor behavior during balance rehabilitation.

2.1.1. Objectives

The objectives of this scoping review are to: (1) determine if Fitts' law, focus of attention or CPF have been used in studies related to balance control among adults; and (2) examine the findings of studies related to balance control among adults that have used the selected motor behavior concept?

2.2. Methods

2.2.1. Study Design

Our study was conducted utilizing a scoping review methodology. A scoping review or a scoping study is defined as "a form of knowledge synthesis that addresses an exploratory research question aimed at mapping key concepts, types of evidence, and gaps in research related to a defined area or field by systematically searching, selecting and synthesizing existing knowledge" (Colquhoun et al., 2014). We utilized the 5-stage framework for conducting scoping reviews (Arksey & O'Malley, 2005). We have incorporated other recommendations to enhance the rigor of our review (Colquhoun et al., 2014; Daudt, van Mossel, & Scott, 2013; Levac, Colquhoun, & O'Brien, 2010). The Preferred Reporting Items for Systematic Reviews and Meta-

Analyses (PRISMA) guidelines have also been applied to inform our scoping review (Moher, Liberati, Tetzlaff, & Altman, 2009).

2.2.2. Research Questions

The questions that the scoping review explored included the following: (i) Have concepts of motor behavior, specifically Fitts' law, focus of attention and the CPF, been used for clinical studies related to balance control among adults. (ii) If so, what are the findings of studies that used these selected motor behavior concepts for balance control among adults?

2.2.3. Literature Search

In this review, we searched for relevant studies using four approaches: (i) using five Medical Subject Headings (MeSH) and subject headings related to our aims; (ii) using twelve keywords that are not MeSH terms or subject headings, but are directly related to the scope of the review, which is to identify studies related to the selected motor behavior concepts and balance control; and (iii) using "citation chaining" search, which involves determining 'key articles' related to the scope of our review, and then searching for all studies that have referenced theses 'key articles'; and, (iv) hand searching reference lists of relevant articles to identify studies related to our objective.

The databases that we searched were PubMed, CINAHL, Scopus and Web of Science. All searches included available records until January 2018. The search strategy did not place limitations on type of study, year or language. All searches were conducted in collaboration with a specialized librarian. In our literature search we used a combination of MeSH terms and keywords to search for studies related to balance control and one (or more) of the selected motor behavior concepts. Search terms related to balance control included 'Postural Balance' OR 'Standing Balance' OR 'Postural'. Search terms related to the selected motor behavior concepts included ‘Fitts’ law’ OR ‘focus of attention’ OR ‘challenge point framework’. Subsequently a search combining balance control terms and motor behavior terms was done to find all related studies. The detailed search strategy is shown in Appendix A. For our other search approach ‘citation chaining’, we identified seven key articles that we have forward searched any studies that have cited these key articles. These specific articles were chosen because they were the first studies to demonstrate these concepts and are often cited for the selected motor behavior concepts. Details of these key articles are found in Appendix B. Citation chaining search was done using the databases Web of Science and Scopus.

2.2.4. Study Selection

Results of our search were exported to a reference manager software (EndNote X7) for screening. Duplicate results were identified and then excluded prior to commencing screening of results. The study selection process underwent two stages. Stage one involved reviewing the titles and abstracts of the articles. Studies that were related to standing balance and one of the three motor behavior concepts were kept and studies that were not related were excluded. Stage two of the study selection process involved screening the remaining studies by reviewing the full-text of the article to determine eligibility. Two independent reviewers (SA and GG) performed all screening of articles; and in the case of discrepancy, a third reviewer (SP) adjudicated to reach consensus. The eligibility criteria of the articles to be included were the following: (i) studies involving human adults (≥18 years of age); (ii) use of one or more of the selected motor behavior concepts in their study. These motor behavior concepts were limited to Fitts’ law, focus of attention and the CPF. Our definition of ‘use’ was that the motor behavior concept was either empirically tested or reported to guide the methods of the study, and not simply referenced as a part of the discussion; (iii) the motor task in the study was related to standing balance or balance control during standing; and, (iv) original research articles written in English and published in a peer-reviewed journals. Reviews, theses, dissertations, published abstracts and conference proceedings were not included.

2.2.5. Charting the Data

Following screening and determining the included articles a charting process was done to extract the following data: (i) title of study, author(s) name(s) and year published, (ii) purpose of study, (iii) number of participants and their characteristics (e.g., healthy non-disabled, older adults, patients post-stroke, etc.) (iv) concept(s) applied in the study and how were they utilized, (v) balance task(s) performed in study, (vi) results and significance of study. Similar to the study selection process, charting data was done by two independent reviewers (SA and GG) using a standardized data extraction form. In addition, we utilized a seven-category rating scale, established in a previous study by Colquhoun and colleagues (2013), in order to classify the type of theory utilization in each of the found studies. Each of the identified studies that have utilized one of the selected motor behaviour theories was placed into a category based on how the theory was used. Categorizing use of theory was done by reviewing how the study reported the application of the theory and then considering each of the seven categories to determine the most relevant category. A study may fall into more than one category. The seven categories were: (1) Justification: the theory was discussed in the background/literature review/objectives section and was used to support the study design/purpose; (2) Intervention Design: the theory informed the intervention, either conceptually or by specifically influencing the design of the intervention; (3) Pilot testing: theory was utilized within the study to guide pilot testing of the intervention; (4) Evaluation: the theory or constructs outlined in the theory were used to guide outcomes measurement or develop the evaluation strategy; (5) Predictions: at least one stated purpose of the study was to test the influence of a variable predicted to be relevant based on a given theory; (6) Post hoc: theory was utilized in the discussion section for the purposes of supporting or explaining the results of the study; (7) Other. The use of theory or constructs could be placed into any number of the categories that applied (Colquhoun et al., 2013). Data charting was piloted on a random sample of 10 articles (of the included studies) to verify agreement between reviewers. Agreement on charting was >90% prior to beginning the formal extraction of all articles.

2.2.6. Collating, Summarizing and Reporting Results

In order to explore the reviews' two questions, our data synthesis relied on: (i) numerical summary of the studies' outcomes, (ii) qualitative analysis of the findings of studies, (iii) results were organized and summarized quantitatively in tables and also described qualitatively, (iv) commenting on each study's findings and the implications it has on practice, policy and/or research. Subsequently, our data synthesis allowed us to identify whether the motor behavior concepts of interest have been applied to studies related to balance control among adults. Overall, the present review provides a comprehensive description on the impact of the selected motor behavior concepts on the clinical studies related to balance control among adults.

2.3. Results

The initial literature search yielded 3085 references (Figure 2-1). After duplicate references (n=1942) were removed, we identified 1143 records for step I screening (title and abstract review). Of the aforementioned 1143 records, we excluded 987 records, as they were not related to the purpose of our review (e.g., did not use one of the selected motor behavior concepts, did not involve standing balance tasks, etc.). The remaining 156 records were reviewed in the step II screening (full-text review). After screening the full-text of 156 records, a total of 46 studies were included in our review and 110 references were excluded.

When reviewing the 46 studies included in our review, we identified 2 studies related to the CPF, 12 studies related to Fitts' law and 32 studies related to focus of attention. Table 2-1 provides a summary of each of the 46 studies. The majority (n=30 [66%]) of the studies involved participants who were healthy young adults, while other studies involved participants who were healthy older adults (n=7 [16%]), patients post-stroke (n=2 [4%]), patients with Parkinson's (n=4 [8%]), patients with multiple sclerosis (n=1 [2%]) and patients post ankle sprain (n=2 [4%]). The majority (n=25 [55%]) of studies utilized a within-participant design to investigate for any potential differences in balance control. Regarding experimental designs of the 46 studies, the majority (n=42 [92%]) were prospective cohort studies and only three clinical trials were identified in our review.

Table 2-2 provides a summary of the nine categories of type of theory used. We identified 37 studies (80%) that used the theory to justify their study and/or provided background on the theory used. All of the included studies used one of the theories to inform their intervention design. We also identified five studies (11%) that used constructs from the theory to guide the evaluation strategy. Finally, we found 38 studies (83%) that used the theory to predict their outcomes as well as used theory to discuss the findings.

Several types of balance tasks were examined in the included studies. The majority of balance tasks involved participants standing on an even surface and maintaining postural stability or controlling center of pressure (COP) (n=20 [44%]). Other studies (n=13 [28%]) investigated postural stability while performing an upper or a lower extremity movement. Also, maintaining balance while performing a balance-challenging task (e.g., standing on an inflated disk or a stabilometer) was investigated by a number of studies (n=13 [28%]). The measures of postural stability varied between studies; however, COP displacement was predominantly used (n=25) followed by total time participant was able to maintain balance (n=2).

2.3.1. Challenge Point Framework

Two studies related to the CPF were found (Table 2-3). The first study by Akizuki and Ohashi (2015) aimed to clarify the functional task difficulty that corresponds to the CPF's optimal challenge point (Akizuki & Ohashi, 2015). The authors used the National Aeronautics and Space Administration-Task Load Index (NASA-TLX) and measured salivary alpha-amylase. Participants in the study were asked to maintain postural stability on the Biodex stability system, which has an alterable level of difficulty when standing. Results showed that there was a significant effect of difficulty level. The authors concluded that the CPF was helpful in identifying the gap between functional task difficulty and the optimal challenge point during skill training (Akizuki & Ohashi, 2015). The second study to use the CPF was by Pollock et al. (2014). In this case series the CPF was used to help design a therapeutic program for retraining people post-stroke in multidirectional stepping reactions to improve community-level walking balance. The results of the study showed that after training participants improved their walking balance and movement kinematics. These improvements were maintained 1 year following completion of the study. The authors concluded that the CPF approach in the retraining of stepping reactions improved community-level walking balance in people with chronic stroke. Further, the CPF provides a good theoretical framework for progression of functional task training in the field of neuro-rehabilitation (Pollock et al., 2014).

2.3.2. Fitts' Law

We identified twelve studies related to the scope of our review that utilized Fitts' law (Table 2-4). Based on the balance task used in the study, we have divided the studies into three categories. The first category of studies (n=7) involved participants standing while performing an aiming movement (lower or upper extremity). The second category of studies (n=4) involved participants standing and controlling COP. The third category of studies (n=1) involved participants standing while maintaining balance on a balance wedge.

2.3.2.1. Studies that involve standing while performing an aiming movement. Two studies by Berrigan and colleagues, that share similar objectives and methodology, were identified (Berrigan, Simoneau, Martin, & Teasdale, 2006; Berrigan, Simoneau, Tremblay, Hue, & Teasdale, 2006). In one study, researchers recruited healthy young adults only, while the other study recruited young adults with different body mass indices (BMI). Both studies aimed to compare differences in performance and postural control during standing and sitting while performing an upper extremity Fitts' task. In the first study the authors found that posture (sitting or standing) had a significant main effect on COP (Berrigan, et al., 2006a). In the second study, the authors found that the difficulty of the task and BMI have a significant effect main effect on COP displacement (Berrigan, et al., 2006b).

Other studies have used Fitts' law to investigate anticipatory postural adjustments (APAs) while performing a lower extremity aiming movement. In a study by Duarte and Latash (2007) the authors used a force platform to determine measures of APAs while subjects performed lower extremity aiming movements. The results of the study showed that MT scaled with ID but across different distances. Also, they reported that changes in task parameters (W and A of Fitts' task) led to proportional changes in movement speed and COP variability. The authors concluded that the speed–accuracy trade-off in a task with postural adjustments originates at the level of movement planning (Duarte & Latash, 2007). In a study by Bertucco and Cesari (2010), the authors used similar methods. Their results corroborated the findings by

Duarte and Latash (2007). Further, Bertucco and Cesari (2010) reported that APA duration scaled with movement amplitude as the onset of APAs occurred earlier for longer amplitude than at the shorter amplitudes. Also, APA magnitude scaled with movement amplitude, with increased activation as ID increased (Bertucco & Cesari, 2010).

Postural adjustments have also been investigated while performing upper extremity movements. Bonnetblanc and colleagues (2004) reported that when performing an upper extremity Fitts' task, target width has a significant effect on APAs. It was found that the magnitude of APAs decreased with decreasing target width (Bonnetblanc, Martin, & Teasdale, 2004). In another study by Bertucco and colleagues (2013) the authors reported that APA measures scale with the ID of the Fitts' task. Further, the authors reported that MT scaled linearly with ID; however, the scaling was different between movement amplitudes, which is a common finding among other studies of Fitts' law and APAs (Bertucco, Cesari, & Latash, 2013). Juras and Slomka (2013) also investigated APAs while performing a Fitts' task. However, the authors reported no significant effect of Fitts' law parameters on measures of APAs (Juras & Slomka, 2013).

2.3.2.2. Studies that involve standing and controlling COP. Several studies (n=4) were identified that have used Fitts' law during a task that involves controlling COP. In a study by Danion and colleagues (1999), the authors recruited subjects who were tasked to shift their weight distribution using their lower extremities in order to alternate position of COP. The results of this study showed that there was a scaling effect as MT increased as a linear function of ID in accordance to Fitts' law but only within each amplitude condition (Danion, Duarte, & Grosjean, 1999). In a study by Duarte and Freitas (2005), the authors reported similar findings. For the same movement amplitude, MT significantly increased with the ratio between movement

A and target W, as predicted by Fitts' law. However, for different movement amplitudes, the regression lines had different slopes (Duarte & Freitas, 2005). In the study by Freitas and colleagues (2006), the authors reported similar findings to the aforementioned studies. The authors found that with the decrease in target W, participants performed significantly slower. Also, MT scaled with ID, but the scaling effect differed between movement amplitudes (Freitas, Duarte, & Latash, 2006). In the study by de Vries et al. (2014), the authors compared weight transfer strategies between young and older adults, while controlling COP in a Fitts' task. The results showed that there were significant effects of W, A and age on MT and COP displacement (de Vries et al., 2014).

2.3.2.3. Studies that involve maintaining balance on a balance wedge. Ferraye et al. (2014) used Fitts' law to control for the difficulty of a balance task. The aim of the study was to investigate the cerebral structure involved in dynamic balance by using motor imagery. However, in one part of the study participants performed a balance task, which involved balancing on a balance wedge while controlling a laser pointer (attached to balance wedge) to aim at different sized targets. The study reported that, as predicted from Fitts' law, MT correlated linearly with ID for the balance task (Ferraye et al., 2014).

2.3.3. Focus of Attention

Thirty-two studies investigating balance and the focus of attention concept were identified using the present search criteria (Table 2-5). We have divided the studies into three categories, based on the balance task used in the study. The first category, which encompasses the majority of studies (n=18), involved participants standing and attempting to maintain postural stability. Several of these studies utilized stable and unstable surfaces (e.g., inflated disk) to challenge participants, while others utilized the Sensory Organization Test (Nashner & Peters, 1990), which uses several conditions to challenge standing balance. The second category of studies involved participants balancing on a stabilometer (n=9). The last category involved supra-postural tasks while adopting different foci of attention (n=6).

2.3.3.1. Studies that involve standing and maintaining postural stability. Beck and Almeida (2017) sought to investigate the effects of different foci of attention among patients with Parkinson's disease, and how it is related to being on or off medications for Parkinson's. The authors reported that COP displacement was significantly affected by focus of attention, with an internal focus of attention (IFA) yielding more stability. However, this finding was only found when patients were off medications (Beck & Almeida, 2017).

In a study by Choi and colleagues (2015) the authors used electroencephalography (EEG) as a form of an external focus of attention (EFA) among participants attempting to stand on an unstable surface (foam pad) while measuring COP displacement. Results showed that when participants adopted an EFA, postural sway decreased significantly compared to IFA and control (no focus) conditions (Choi, Lee, & Park, 2015).

In a randomized clinical trial (RCT) by de Bruin et al. (2009) the authors recruited healthy older adults and administered a twice weekly, 5-week functional balance training program. Participants were divided into IFA and EFA groups. Results showed that there was an overall improvement in balance among both groups; however, IFA and EFA failed to have a significant effect on standing balance tasks. Both groups (IFA and EFA) similarly improved in balance task performance within 5 weeks (de Bruin, Swanenburg, Betschon, & Murer, 2009).

In a study by dos Anjos and colleagues (2016), the authors wanted to examine different types of visual feedback during quiet standing and maintaining postural stability. Subjects either stood with their eyes open (control), stood while controlling their COP (IFA) or stood while controlling a laser pointer on a target (EFA). Results showed that there were significant differences between the three conditions in COP displacement as an IFA had smaller COP displacement than the other two conditions (dos Anjos, Lemos, & Imbiriba, 2016).

Hosseini et al. (2011) and Ghayor et al. (2014) conducted two similar studies, which investigated the effects of different attentional foci while performing static and dynamic standing balance tasks. The study by Hosseini et al. (2011) involved healthy older adults and they reported that there were no significant differences between IFA and EFA conditions during the static balance task. However, in the dynamic balance task adopting an EFA led to significantly better performance compared to IFA (Hosseini, Allahyari, Rostamkhani, & Jalili, 2011). In the study by Ghayor et al. (2014), which involved female patients with multiple sclerosis, their results showed that an EFA led to significantly better performance in measures of dynamic and static balance (Ghayor, Bagherli, & Aslankhani, 2014). Jehu et al. (2015) examined the influence of attention prioritization. In their study subjects were asked to either focus on posture (IFA) or focus on a reaction time (RT) task (EFA). Results showed that prioritizing to RT (EFA) produced faster RTs and decreased COP displacement compared to prioritizing posture (IFA) (Jehu, Desponts, Paquet, & Lajoie, 2015).

Landers and colleagues conducted two studies (2005 and 2016) that involved patients with Parkinson's disease. In their earlier study, Landers et al. (2005) wanted to determine the generalizability of the focus of attention concepts among patients with Parkinson's disease. Subjects were asked to maintain standing balance while adopting an EFA, IFA or control. The results showed that there were no significant differences between conditions. However, when analyzing a section of the participants (subjects with fall history), one of the balance tasks demonstrated that when adopting an EFA, participants' equilibrium scores were significantly better than the other two conditions (Landers et al., 2005). In the subsequent study by Landers et al. (2016), the authors conducted an RCT to compare the effects of different attentional foci among individuals with Parkinson's disease. Subjects were divided into four groups: three groups who received intervention and one was control. The three groups that received intervention either adopted an EFA, IFA or no instruction. Results yielded no differences among the groups in trajectory of intervention over the course of the RCT for all outcome measures. While all four groups improved, there was no difference between the groups, including the no intervention group (control) (Landers, Hatlevig, Davis, Richards, & Rosenlof, 2016).

Laufer et al. (2007) and Rotem-Lehrer and Laufer (2007) conducted two very similar studies that involved patients post ankle sprain. The two studies provided a short-term (2-3 days) balance-training program, followed by a retention test that utilized different attentional foci. Subjects were divided into two groups: an IFA and an EFA, and were tested using the Biodex balance system to determine their stability index. The results of both studies showed that the EFA group had significantly better stability compared to the IFA group (Laufer et al., 2007; Rotem-Lehrer & Laufer, 2007).

Other studies investigated the effects of performing a continuous cognitive task versus an IFA or EFA. Polskaia et al. (2015) and Richer et al. (2017a and 2017b) conducted similar studies to compare the different foci of attention and a continuous cognitive task during postural control. Their results were also similar, as they have shown that performing a continuous cognitive task yields better postural control compared to an IFA or an EFA (Polskaia, Richer, Dionne, & Lajoie, 2015; Richer, Polskaia, & Lajoie, 2017; Richer, Saunders, Polskaia, & Lajoie, 2017). However, Richer et al. (2017b) reported that an EFA also led to better postural control compared to an IFA, although a continuous postural task was more efficient.

Wulf and colleagues conducted three studies that involved standing and maintaining postural stability (Wulf, 2008; Wulf et al., 2009; Wulf, Tollner, & Shea, 2007). In the study by Wulf et al. (2007), the authors aimed to investigate the effects of an IFA or an EFA on postural control while systematically varying the surface stability and limb support (double and single). The study's task involved standing on different stability surfaces while determining COP displacement. Results showed that there was a significant effect of focus of attention on COP displacement, as an EFA led to smaller COP sway compared to IFA or control conditions. Wulf (2008) investigated the focus of attention concept among elite acrobats. Subjects were asked to maintain standing while on an unstable surface. The author found that there were no significant differences between IFA or EFA on COP sway. Wulf and colleagues (2009) also investigated the attentional focus concepts among patients with Parkinson's disease. Subjects were asked to stand on an unstable surface that is placed on top of a force platform to determine COP sway. Subjects adopted different foci of attention while standing. The results showed that COP sway was significantly smaller under EFA compared to other conditions (IFA or no attentional instruction).

Yeh et al. (2016) also conducted a study that used focus of attention while participants were asked to maintain postural stability. The authors wanted to investigate whether there is an age-related difference in relation to the adherence to the specific instructional constraints under EFA and IFA conditions, while manipulating the presence and absence of visual feedback. Their results provided evidence that for young adults during IFA conditions there was no difference between presence and absence of visual feedback. However, during EFA conditions, COP sway variability significantly decreased when feedback was removed. With older adults, during IFA, presence and absence of feedback was significant, as sway variability significantly reduced when feedback was removed. Similarly, in the EFA condition sway variability significantly reduced when feedback was removed (Yeh, Cinelli, Lyons, & Lee, 2016).

2.3.3.2. Studies that involve balancing on a stabilometer. Wulf and colleagues conducted four studies and all of these studies involved healthy young adults attempting to maintain balance on a stabilometer while adopting different foci of attention (Wulf et al., 1998; Wulf & McNevin, 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001). These studies shared similar findings as they all report that adopting an EFA led to better performance when balancing on the stabilometer. One study reported that when participants were trained on both foci of attention and given the choice of one to perform a retention test, the majority (>70%) of participants chose an EFA (Wulf, Shea, et al., 2001). In another study, Wulf and McNevin (2003), reported that the positive benefits of an EFA could not be replicated by an attention demanding (repeating a story out loud) secondary task.

Balancing on a stabilometer has also been investigated among older adults. Chiviacowsky et al. (2010) reported that among older adults adopting an EFA led to better time in balance on the stabilometer, compared to an IFA (Chiviacowsky et al., 2010). The benefits of adopting an EFA can also be augmented if the task objective is external. Jackson & Holmes (2011) speculated that if the task objective is external, an EFA would lead to more benefits than if the task objective was internal. Results confirmed the authors' hypothesis, as performance was best when participants adopted an EFA and their task objective was also external (Jackson & Holmes, 2011). McNevin and colleagues (2003) have also reported that the distance at which participants direct their focus of attention has an effect on performance. The authors reported that when participants were balancing on a stabilometer, the best performance was seen when the point of external focus was further away from the body compared to an IFA or a more close EFA point (McNevin et al., 2003).

The benefits of adopting an EFA can also be obtained via feedback. In a study by Shea & Wulf (1999), the authors provided feedback to participants in the form of a computer monitor shown to them concurrently with their performance. The monitor showed two horizontal lines on the left and right sides of the screen that represented the actual position of the platform of the stabilometer used in the study. Subjects were told that the two lines either represented the stabilometer platform (EFA), or represented their feet (IFA). Results showed that the EFA outperformed the IFA group (Shea & Wulf, 1999).

2.3.3.3. Studies that involve a supra-postural task. We identified six studies that investigated focus of attention while subjects performed a suprapostural task (e.g., balancing a long wooden stick horizontally) and attempted to maintain postural stability or balance on a stabilometer. Four studies utilized a force platform to assess postural stability while performing a supra-postural task and adopting different foci of attention. Cluff et al. (2010) reported that no significant differences were found between subjects who adopted an EFA versus those who adopted an IFA when performing a supra-postural task (Cluff, Gharib, & Balasubramaniam, 2010). However, three other studies reported that subjects who adopted an EFA showed better postural stability, as measured by COP sway, compared to performing with an IFA (McNevin, Weir, & Quinn, 2013; McNevin & Wulf, 2002; Wulf et al., 2004). We also found two studies that investigated different foci of attention during a supra-postural task while balancing on as stabilometer. Both studies reported that an EFA improved performance when balancing on a stabilometer and performing a supra-postural task (Huang, Zhao, & Hwang, 2014; Wulf et al., 2003).

2.4. Discussion

The present study is the first scoping review to synthesize the available evidence related to Fitts' law, focus of attention and the CPF among studies examining balance control among adults. We have chosen to conduct a scoping review as it provides a better representation of the literature because it addresses broader topics. Furthermore, scoping reviews report and synthesize from different types of study designs and are not limited to RCTs. Reporting from different study designs is especially important given that our results (n=46) included only two RCTs. We followed the recommendations of Arksey and O'Malley's framework (2005) and the subsequent published updates on conducting scoping reviews to enhance the rigor of our study (Colquhoun et al., 2014; Daudt et al., 2013; Levac et al., 2010). Our aims were to identify and synthesize the findings of studies related to standing balance among adults that have used Fitts' law, focus of attention or CPF. We also intended to review the potential advantages of using the selected motor behavior concepts in studies related to balance control.

We found 46 records that fit our selection criteria. One finding that was evident is that most studies recruited healthy young adults, with only a few (n=15) studies recruiting subjects with balance impairments (e.g., patients post-stroke, older adults, etc.). Further, we found only a few (n=3) clinical trials that have reported the use of these motor behavior concepts. This finding is in line with previous research that suggests that some motor behavior concepts are not regularly used in clinical practice (Durham et al., 2009; Johnson et al., 2013; Porter et al., 2010; Shumway-Cook & Woollacott, 2012). For example, several studies reported that although the benefits of adopting an external focus of attention have been reported frequently, there seems to be a lag in clinical and community uptake of the focus of attention concept (Durham et al., 2009; Johnson et al., 2013; Porter et al., 2010).

The categories of how the motor behavior concepts were used ranged from intervention design to predictions of outcomes and use of concepts to explain results in the discussion section. Although two categories (pilot testing and other) of theory utilization were not identified in the studies identified in this review (see Table 2-2), the breadth of theory utilization remains comprehensive as most categories were counted in a high number of studies. We found a variety of balance tasks during standing were used across the included studies. The variety of balance tasks suggests that the selected concepts of motor behavior are applicable to different forms of balance tasks.

2.4.1. Challenge Point Framework

The two studies that utilized the CPF lend strong support to applying this framework for motor skill training. Akizuki and Ohashi (2015) were able to support the existence of the optimal challenge point of the CPF via measuring alpha-amylase and the performance on the NASA-TLX. The ability to quantify the optimal challenge point of the CPF provides further support for this framework. Determining the optimal challenge point provides motor skill trainers with the ability to know the gap between functional task difficulty and the optimal challenge point, which is important during motor skill training. However, more research is required in this field in order to investigate more ways for determining the optimal challenge point. Pollock et al. (2014) reported that using the CPF was helpful for providing a theoretical framework for progressing balance skill training among patients post-stroke. However, as the authors also remark, their study findings should be interpreted with caution given the small number of participants and the lack of control subjects. Yet despite these limitations, the overall findings of their study are encouraging, especially that other studies that included subjects with neurological symptoms have reported on the benefits of using the CPF for motor skill training (Onla-or & Winstein, 2008). Based on the aforementioned studies, using the CPF to guide balance training appears to be promising. Future research into utilizing the CPF in clinical studies is warranted in order to further validate its value.

2.4.2. Fitts' Law

The results of our review also support the use of Fitts' law as a method for controlling the difficulty of motor tasks related to balance control. The two studies by Berrigan and colleagues (2006a & 2006b) have reported important findings related to Fitts' law parameters when performing an upper extremity aiming task and how it affects COP. The authors reported that the difficulty of a reaching task cannot be solely determined by the task's ID as posture (standing or seating) during aiming led to different responses in MT and COP displacement. The previous finding, that task difficulty cannot be determined solely by ID of the targets, is important to clinicians involved in balance training as emphasizing postures and position should always be taken into consideration in order to control the difficulty of balance training. In their second study, Berrigan et al. (2006b) reported that an increased BMI led to increasing task difficulty, even though the ID of the task was constant. The relation between BMI and task difficulty is also important to clinicians and should be taken into account when providing balance training.

Fitts' law has also been used in two studies as a method to control the difficulty of the tasks performed in their experiments. In one study, de Vries et al. (2014) reported that older adults compared to young adults, require more time to perform a weight-shifting task and their movements were less fluent and accurate, especially with increasing difficulty. The use of Fitts' law to design the task in this study was helpful in determining these differences between older and young adults. Similarly, Ferraye et al. (2014) used Fitts' law to control the difficulty of the dynamic balance task in their study. As predicted by Fitts' law the authors reported that MT correlated linearly with ID. Their finding corroborates previous studies that have demonstrated the robustness of Fitts' law and that it holds true in different contexts (Plamondon & Alimi, 1997).

We have identified eight studies that have investigated APAs while utilizing Fitts' law (Bertucco & Cesari, 2010; Bertucco et al., 2013; Bonnetblanc et al., 2004; Danion et al., 1999; Duarte & Freitas, 2005; Duarte & Latash, 2007; Freitas et al., 2006; Juras & Slomka, 2013). The majority of these studies report similar findings. One significant finding that was reported by most of these studies is that measures of APAs have a significant relationship with Fitts' law parameters. It was found that although Fitts' law did not hold, there was a scaling effect between MT and ID but not in all conditions. Studies reported that MT increased as a linear function of increasing ID in accordance to Fitts' law but only within each amplitude condition. Further, it was reported that changes in task parameters (i.e., changes in ID), led to proportional changes in measures of APAs prior to movement initiation. Finally, the majority of studies concluded that the findings related to Fitts' law parameters and APAs support the hypothesis that Fitts' law control originates from the level of motor planning, and not at the level of correcting ongoing movements.

As previous research indicates APAs are critical as (1) APAs are the first line of defense against falling (Aruin, 2016; de Azevedo, Claudino, Conceicao, Swarowsky, & Santos, 2016; Kanekar & Aruin, 2014b); and (2) improving APAs leads to better postural control and reduces the risk of falls (Aruin, 2016; Aruin, Kanekar, Lee, & Ganesan, 2015; Kanekar & Aruin, 2014a, 2014b, 2015; Kubicki, Mourey, & Bonnetblanc, 2015; Saito, Yamanaka, Kasahara, & Fukushima, 2014), the findings in our review provide important information for clinicians involved in balance training. For example, Fitts' law could be used as a method for controlling the difficulty of balance training exercises. This could be done by modifying the length of a step and the surface area of a step (similar to Fitts' law's A and W), as means of objectively controlling the training difficulty during balance training. Further, the CPF can be used to relate the skill level of the individual and the difficulty of the Fitts' task in order to identify the optimal challenge point and achieve optimal learning.

2.4.3. Focus of Attention

We identified thirty-two studies related to focus of attention in our review. Our findings provide evidence that adopting an external focus of attention improves performance and learning of motor skills compared to an internal focus of attention. Among the studies we identified, 23 reported that an EFA led to better performance compared to an IFA; whereas only 2 studies reported the benefits of an IFA over an EFA and 7 studies reported no significant differences between EFA and IFA. When examining the studies that have reported that an IFA led to better performance than an EFA we can comment on a few points in their studies that might have led to their findings. In one study the investigators recruited patients with Parkinson's disease and tested subjects when they were off or on their medications (Beck & Almeida, 2017). The results of the study also showed that greater performance is noticed when medications are present and adopting an EFA. In regard to the other study that reported the benefit of an IFA versus an EFA (dos Anjos et al., 2016), the authors used two forms of attentional foci that are both technically an EFA. An EFA is defined as focusing attention on the effects of movement (Wulf et al., 1998; Wulf, McNevin, et al., 2001). In the study by dos Anjos and colleagues (2016), the authors asked subjects to either focus on their COPs or a hand-held laser pointer that moves as they move. Since both foci of attention used in this study are in fact "results of movement" and not focusing on the limb itself, they are both EFAs.

In the studies that have found no difference between an EFA and IFA, some of these studies have reported important outcomes that should be discussed. In the study by Landers et al. (2005) the general results did not report any significant differences between IFA, EFA or control conditions. However, in post-hoc analyses participants with a fall history showed better performance when adopting an EFA (Landers et al., 2005). In the other study by Landers and colleagues (2016), the authors reported that there were no significant differences between an IFA and an EFA. However, the subjects who did not receive balance therapy (control) also did not show a significant difference when compared to the other groups who received treatment (Landers et al., 2016). This suggests that perhaps the whole balance-training program in this RCT was not effective. Finally, in the study by Wulf (2008) the author reported no significant differences between an IFA and EFA were found. However, the participants' performance was best when they were asked to perform under control (no instruction) condition. The population recruited in this study was highly trained world-class acrobats. The author speculated that the participants' performance was best in control condition because they were free to adopt their "normal" focus of attention. The author concluded that there may be a limit to the focus of attention concept among top-level performers (Wulf, 2008).

Despite the few studies that have not supported the benefits of adopting an EFA over an IFA, the majority of the studies (>70%) found in our review indicate that an EFA is more beneficial for motor performance compared to an IFA or no instruction (control). Further, the focus of attention concept was utilized among different populations including healthy young and older adults, patients with Parkinson's disease, patients with multiple sclerosis and those with musculoskeletal injuries (e.g., ankle sprain). Our review also found evidence that the majority of participants who experience or train using different foci of attention show a preference for an

EFA, as reported by Wulf et al. (2001b). The benefits of adopting an EFA also extend to improving the performance on RT tasks as shown in the study by Jehu et al. (2015). The benefits of adopting an EFA can also be obtained via performing a supra-postural task and via feedback or direct instructions (Choi et al., 2015; Huang et al., 2014; McNevin et al., 2013; McNevin & Wulf, 2002; Shea & Wulf, 1999; Wulf et al., 2004; Wulf et al., 2003; Yeh et al., 2016). In order to achieve the highest advantages from adopting an EFA, our review indicates two points: (1) the task objective should also be external when adopting an EFA; and (2) the more distant the point of focus when adopting an EFA, the better the performance. Lastly, there is a major knowledge gap identified from this review. The majority (~75%) of focus of attention studies recruited individuals who are healthy adults. It is recommended that future research investigate the effect of different foci of attention among people with balance impairment in order to ascertain its benefit for clinical practice.

This scoping review is the first methodological review to investigate the use of the three motor behavior concepts (Fitts' law, focus of attention and CPF) in balance control studies. It provides an overall synthesis of results related to the scope of the review. One limitation in this review is that we do not include an assessment of quality of studies. However, given the diversity of studies included in the review and the different methodologies used for each study, it is not possible to utilize one quality assessment form for all studies.

2.5. Conclusions

In conclusion, the use of CPF, Fitts' law and focus of attention in studies related to balance control appears to be useful. Future research should include more participants who have specific balance impairments in order to generate recommendations that can be generalized to such populations. Further, the utilization of these motor behavior concepts in clinical trials, such as RCTs, is warranted in order to determine their efficacy for clinical use. Future studies should consider utilizing these motor behavior concepts when designing clinical trial studies to better understand the impact of these concepts among clinical populations. The CPF appears to be a useful method for designing a progressive therapeutic program. Fitts' law can be used a tool for controlling the difficulty of motor tasks during balance. Finally, adopting an EFA while performing a balance task improves performance and learning of motor skills.

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Table 2-1. Summary of Studies

Study	Participants characteristics	N	Age	Balance activity
Challenge Point Framework				
Akizuki & Ohashi, 2015	Healthy young adults	60	Mean age= 22.5 ± 2.25 y	Standing and maintain postural stability
Pollock et al., 2014	Patients post-stroke	4	Age range= 53-68 y	Multidirectional stepping reactions
Fitts' Law				
Berrigan et al., 2006a	Healthy young adults	12	Mean age= 26 y	Standing while performing aiming movement with upper limb
Berrigan et al., 2006b	a. Young adults with normal BMI	8	Mean age= 26.1 y	Standing while performing aiming movement with upper limb
	b. Young adults with BMI>30.5	9	Mean age= 38.7 y	
Bertucco & Cesari, 2010	Healthy young adults (professional dancers)	12	Mean age= 26 ± 8 y	Standing while performing aiming movement with lower limb
Bertucco et al., 2013	Healthy young adults	10	Mean age= 27 ± 4 y	Standing while performing aiming movement with upper limb
Bonnetblanc et al., 2004	Healthy young adults	8	Mean age= 26 y	Standing while performing aiming movement with upper limb
Danion et al., 1999	Healthy young adults	6	Mean age= 28.5 ± 3.6 y	Standing on a force platform and controlling COP
de Vries et al., 2014	a. Healthy young adults b. Healthy older adults	12 9	Mean age= 20.9 ± 0.5 y Mean age= 70.3 ± 6.9 y	Standing on a force platform and controlling COP
Duarte & Freitas, 2005	Healthy young adults	11	Mean age= 28 ± 6 y	Standing on a force platform and controlling COP
Duarte & Latash, 2007	Healthy young adults	10	Mean age= 32 ± 8 y	Standing while performing aiming movement with lower limb
Ferraye et al., 2014	Healthy young adults	20	Mean age= 20.2 ± 1.8 y	Balancing on a balance wedge
Freitas et al., 2006	Healthy young adults	10	Mean age= 31 ± 6 y	Standing on force platform and controlling COP

Juras & Slomka, 2013	Healthy young adults	16	Mean age= 24.1 ± 1.9 y	Standing while performing aiming movement with upper limb
Focus of Attention				
Beck & Almeida, 2017	Patients with Parkinson's disease	19	Mean age= 71.4 ± 6.1 y	Standing and maintain postural stability
Chiviacowsky et al., 2010	Healthy older adults	32	Mean age= 69.4 ± 6.6 y	Balancing on a stabilometer
Choi et al., 2015	Patients post-stroke	21	Age range= 41-75 y	Balancing on an unstable surface (foam)
Cluff et al., 2010	Healthy young adults	10	Age range= 19-27 y	Standing on a force platform while doing a suprapostural task
de Bruin et al., 2009	Healthy older adults	26	Mean age= 81 y	Standing and maintain postural stability
dos Anjos et al., 2016	Healthy young adults	26	Mean age= 23.5 ± 3.6 y	Standing and maintain postural stability
Ghayor et al., 2014	Patients with multiple sclerosis	45	Age range= 20-45 y	Standing while performing a static and a dynamic balance task
Hosseini et al., 2011	Healthy older adults	40	Mean age= 62 ± 3 y	Standing while performing a static and a dynamic balance task
Huang et al., 2014	Healthy young adults	12	Mean age= 22.6 ± 2.2 y	Balancing on a stabilometer and also doing a suprapostural task
Jackson & Holmes, 2011	Healthy young adults	36	Mean age 21.4 y	Balancing on a stabilometer
Jehu et al., 2015	Healthy young adults	20	Mean age 21.6 ± 2.3 y	Standing and maintain postural stability
Landers et al., 2005	Patients with Parkinson's disease	22	Mean age= 72.2 y	Balance assessment (Sensory Organization Test)
Landers et al., 2016	Patients with Parkinson's disease	49	Mean age= 71.7 y	Balance assessment (Sensory Organization Test)
Laufer et al., 2007	Patients post ankle sprain	40	Age range= 19-33 y	Standing and maintain postural stability
McNevin & Wulf 2002	Healthy young adults	19	Age range= 26-54 y	Standing while doing a suprapostural task
McNevin et al., 2003	Healthy young adults	40	Not reported	Balancing on a stabilometer
McNevin et al., 2013	a. Healthy young adults b. Healthy older adults	12 12	Mean age= 20.98 y Mean age= 70.8 y	Standing on a force platform while doing a suprapostural task
Polskaia et al., 2015	Healthy young adults	20	Mean age= 21.4 ± 2.6 y	Standing and maintain postural stability

Richer et al., 2017a	Healthy older adults	16	Mean age= 71.9 ± 4.32 y	Standing and maintain postural stability
Richer et al., 2017b	Healthy young adults	25	Mean age= 20.7 ± 2.76 y	Standing and maintain postural stability
Rotem-Lehrer &Laufer, 2007	Patients post ankle sprain	36	Mean age= 20.9 y	Standing and maintain postural stability
Shea & Wulf, 1999	Healthy young adults	32	Not reported	Balancing on a stabilometer
Wulf et al., 1998	Exp. I. Healthy young adults	33	Mean age=25 y	Balancing on a ski-simulator
	Exp. II. Healthy young adults	16	Not reported	Balancing on a stabilometer
Wulf et al., 2001a	Healthy young adults	28	Not reported	Balancing on a stabilometer
Wulf et al., 2001b	Exp. I. Healthy young adults	17	Not reported	
	Exp. II. Healthy young adults	20	Not reported	Balancing on a stabilometer
Wulf & McNevin, 2003	Healthy young adults	55	Not reported	Balancing on a stabilometer
Wulf et al., 2003	Exp. I. Healthy young adults	18	Not reported	Balancing on a stabilometer and perform a suprapostural task
	Exp. II. Healthy young adults	29	Not reported	
Wulf et al., 2004	Healthy young adults	32	Not reported	Stand on an unstable surface and perform a suprapostural task
Wulf et al., 2007	Exp. I. Healthy young adults	18	Not reported	Standing and maintain postural stability on different surfaces
	Exp. II. Healthy young adults	24	Not reported	
Wulf 2008	Healthy young adults (professional acrobats)	12	Not reported	Stand on an unstable surface
Wulf et al., 2009	Patients with Parkinson's disease	14	Mean age= 71.1 y	Stand on an unstable surface
Yeh et al., 2016	a. Healthy young adults	12	Mean age= 23.7 ± 5.1 y	Standing on force platform and controlling COP
	b. Healthy older adults	12	Mean age= 74.8 ± 5.6 y	

y: years; BMI: body mass index; COP: center of pressure.

Table 2-2. Summary of Categories of Theory Use

Category	Number of times used
Justification	37 (80%)
Intervention Design	46 (100%)
Pilot testing	0
Evaluation	5 (11%)
Predictions	38 (83%)
Post-hoc	38 (83%)
Other	0

Justification: theory is discussed in the background/literature review/objectives section and is used to support study design/purpose; (2) Intervention Design: the theory informed the intervention, either conceptually or by specifically influencing the design of the intervention; (3) Pilot testing: theory was utilized within the study to guide pilot testing of the intervention; (4) Evaluation: the theory or constructs outlined in the theory were used to guide outcomes measurement or develop the evaluation strategy; (5) Predictions: at least one stated purpose of the study was to test the influence of a variable predicted to be relevant based on a given theory; (6) Post hoc: theory was discussed in the discussion section for the purposes of supporting or explaining the results of the study; (7) Other. The use of theory or constructs could be placed into any number of the categories that applied.

Table 2-3. Findings of Studies Related to CPF

Study	Purpose of study	Study Findings
Akizuki & Ohashi, 2015	The CPF was used to determine the optimal challenge point for a balance-training program among four groups.	Results of ANOVA showed that there is a significant ($p<0.001$) main effect of group (i.e., difficulty level) with a partial $\eta^2 = 0.664$; and a main effect of block of training $\eta^2= 0.369$. Authors concluded that the CPF was helpful in identifying the gap between functional task difficulty and the optimal challenge point during skill training.
Pollock et al., 2014	The CPF was used to control the progression of task difficulty in the therapeutic program.	Authors concluded that the CPF provides a good theoretical framework for progression of functional task training in the field of neuro-rehabilitation.

CPF: challenge point framework; ANOVA: analysis of variance.

Table 2-4. Findings of Studies Related to Fitts' Law

Study	Purpose of study	Study Findings
Berrigan et al., 2006a	To compare differences in performance and postural control during standing and sitting while performing an upper extremity Fitts' task.	ANOVA analysis showed that ID and posture have significant main effects on MT ($p<0.05$). Decomposition analysis of MT showed that there was no significant effect of posture on individual MTs except for the highest ID. ANOVA analysis of COP displacement showed a significant main effect of posture ($p<0.001$). Authors concluded that the difficulty of aiming cannot be solely determined by the ID in Fitts' law.
Berrigan et al., 2006b	To compare differences in performance and postural control among individuals with different BMIs while performing an upper extremity Fitts' task.	ANOVA analysis showed that both ID and BMI have significant main effects on MT ($p<0.05$). Decomposition analysis of MT showed that for the most difficult IDs, MTs increased significantly ($p<0.05$) for obese group compared to lean group. ANOVA analysis of COP showed that group and IDs had a significant main effect on forward and backward COP displacement ($p<0.05$). Study concluded that BMI appears to affect MT.
Bertucco & Cesari, 2010	To investigate the changes associated with APAs with different Fitts' law parameters while performing a lower extremity Fitts' task.	MT and peak velocity were found to scale with ID only for the same movement amplitude, but across multiple target widths, correlation coefficient r varied from 0.97-0.99 ($p<0.01$). APA duration scaled with movement amplitude as the onset of APAs occurred earlier at the longer distances than at the shorter distances ($p<0.05$). APA magnitude also scaled with movement amplitude, with increased activation as ID increased ($p<0.05$).
Bertucco et al., 2013	To examine the relation between early postural adjustments and parameters of a Fitts' task while performing an upper extremity Fitts' task.	MT scaled linearly with ID. Also, A and ID had a significant effect on MT ($p<0.001$). When fitting data for each A with Fitts' law equation, the correlation coefficients r were 0.98 and 0.99 ($p < 0.01$) for the 2 As. Similar trends were also found for peak velocity as A and ID had significant main effect on peak velocity ($p<0.001$).
Bonnetblanc et al., 2004	To examine whether a Fitts' task would influence APAs, while performing an upper extremity Fitts' task.	Results showed a significant ($p<0.05$) main effect of target width on APAs as measured by EMG. It was found that the magnitude of the integrated EMG activity of lower limb muscles decreased with decreasing target width.

Danion et al., 1999	To determine how fast and accurate people could displace their COP between targets of varying distance and size,	For each A, MT was an increasing linear function of ID. Regression analysis showed that correlation coefficients were all significant at all As ($r>0.93$, $p<0.01$). ANOVA results showed that ID had a main effect on MT ($p<0.001$). Lastly, regression lines for different As were not parallel.
de Vries et al., 2014	To compare differences in weight transfer strategies between young and older adults, while controlling COP.	Significant ($p < 0.01$) main effects of W, A and age on MT and COP were found. As target W decreased, movement A and age increased this led to MT significantly increasing and accuracy significantly decreasing. Older adults needed more time to perform the study task and their movements were less accurate compared to younger adults, especially with increasing ID.
Duarte & Freitas, 2005	To determine how fast and accurate people could displace their COP between targets of varying distance and size	ANOVA analysis showed that for the same movement A, MT significantly ($p<0.01$) increased with the ratio between movement A and target W, as predicted by Fitts' law. However, for different movement A, the regression lines had different slopes. Authors speculated that the differences in slopes are due to the amount of COP variability present during quiet standing.
Duarte & Latash, 2007	To investigate the relation between APAs and Fitts' law parameters while performing a lower extremity Fitts' task.	Findings indicated that there is a scaling effect of MT with both A and W. However, scaling was different across target Ws. Indices of both force and COP variability (APA measures) showed significant positive linear dependences on movement speed with $r>0.91$ ($p<0.0001$).
Ferraye et al., 2014	Aim of study was to investigate the cerebral structure involved in dynamic balance by using motor imagery.	This study used Fitts' law to control the difficulty of a dynamic balance task. The study reported that, as predicted from Fitts' law, MT correlated linearly with ID for the dynamic balance task ($r^2=0.9\pm0.1$).
Freitas et al., 2006	To investigate joint angle co-variation patterns during whole-body actions performed by standing persons.	Authors reported that with the decrease in target W, participants performed significantly ($p<0.05$) slower. MT scaled ($r>0.93$; $p<0.01$) with ID but the scaling effect differed between movement As.
Juras & Slomka, 2013	To explore the effects of accuracy constraints on the characteristics of APAs.	No significant effect for target W on measures of APA.

ANOVA: analysis of variance; ID: index of difficulty; MT: movement time; COP: center of pressure; BMI: body mass index; APA: anticipatory postural adjustment; A: movement amplitude; W: target width; EMG: electromyography.

Table 2-5. Findings of Studies Related to Focus of Attention

Study	Purpose of study	Study Findings
Beck & Almeida, 2017	To compare the effects of adopting different foci of attention and how that interacts with being on or off medications for patients with Parkinson's disease.	ANOVA analysis showed that when off medications there was a significant main effect of focus of attention for COP displacement ($p<0.05$), with the least amount of COP sway during IFA. Further, ANOVA analysis showed that there was a main effect of being on/off medication ($p<0.05$), with sway displacement significantly greater when on medications. Study concluded that when patients were off medications an EFA is detrimental as it may prevent automaticity.
Chiviacowsky et al., 2010	To investigate the effects of different foci of attention among older adults, while balancing on a stabilometer.	Results showed that when adopting an EFA the overall time in balance (maintain horizontal position) on the stabilometer was significantly longer for the external focus group ($p<0.05$)
Choi et al., 2015	To assess the use of EEG feedback as an EFA during balance on an unstable surface. Participants performed balance task under 3 conditions: control, IFA and EFA.	Results showed that when participants adopted an EFA, postural sway decreased significantly compared to IFA and control conditions ($p<0.05$).
Cluff et al., 2010	To examine the effects of different foci of attention on COP trajectories during a supra-postural task.	Results did not show a significant effect of either condition (IFA or EFA) on standing balance performance or the supra-postural task.
de Bruin et al., 2009	To compare two different types of attentional focus instructions while performing standing balance tasks.	Results showed that IFA and EFA failed to have a significant effect on standing balance tasks. Both groups (IFA and EFA) similarly improved in task performance within 5 weeks.
dos Anjos et al., 2016	To examine different types of visual feedback during the control of standing balance. Three conditions were used for this study: IFA, EFA and control.	Results showed that there were significant differences ($p<0.01$) between the three conditions in COP displacement. Post-hoc tests indicated that an IFA had smaller COP displacement than other two conditions.
Ghayor et al., 2014	To investigate the effects of internal and external attentional foci of attention during static and dynamic balance tasks.	Results showed that participants in the EFA group had significantly better ($p<0.05$) performance in measures of dynamic and static balance compared to the two other groups, IFA and control.
Hosseini et al., 2011	To investigate the effects of internal and external attentional foci of attention during	Results indicated that there were no significant differences between IFA and EFA during the static balance task. However, in the dynamic

	static and dynamic balance tasks.	balance task adopting an EFA led to significantly better ($p<0.05$) performance compared to IFA.
Huang et al., 2014	To investigate the effects of different foci of attention on postural and supra-postural tasks, while participants attempt to balance on a stabilometer.	Postural control with an EFA caused superior force-matching performance, more complex ankle movement, and stronger kinematic coupling between the ankle and stabilometer movements than postural control with an IFA.
Jackson & Holmes, 2011	To determine if the reported benefits of an EFA found in previous studies is due to the focus-of-attention direction itself, or the relative consistency with the task objective.	Results showed that there was a significant effect of focus of attention and task objective ($p<0.05$). Post-hoc analyses showed that an EFA is most effective when the task objective is also external ($p<0.05$).
Jehu et al., 2015	To examine the influence of attention prioritization, subjects were asked to either focus on posture (IFA) or focus on the RT task (EFA).	Results showed that prioritizing to RT (EFA) produced faster RTs ($p < 0.001$) and decreased COP displacement ($p<0.05$) compared to prioritizing posture (IFA).
Landers et al., 2005	To determine the generalizability of the focus of attention concept among patients with Parkinson's disease. Balance was tested using the Sensory Organization Test, under three conditions: IFA, EFA and control.	Overall, results did not show significant differences between the three conditions. However, when analyzing a section of the participants (subjects with fall history), one of the Sensory Organization Test tasks showed that when adopting an EFA, participants' equilibrium scores were significantly higher ($p<0.05$) than the other two conditions.
Landers et al., 2016	To compare the effects of different attentional foci among individuals with Parkinson's disease following an RCT. Subjects were divided into four groups: three who received intervention and one was control.	Results showed that there were no differences among the groups in trajectory over the course of the RCT for all outcome measures. While all four groups improved, there was no difference among the groups, including the control. Authors speculated that the 4-week balance-training program in this RCT was not effective.
Laufer et al., 2007	To compare different foci of attention during the learning of a balance task among subjects following an ankle sprain injury.	Results showed that subjects who adopted an EFA had significantly ($p<0.05$) more efficient postural control than the IFA group as measured by the Biodex Balance System "Overall Stability Index".
McNevin & Wulf, 2002	To determine whether increased postural stability through the addition of a supra-	The addition of a supra-postural task did not generally result in more efficient performance. However, ANOVA analysis revealed that there

	postural task is due to the supra-postural task itself or due to the attentional focus instruction during the supra-postural task.	was a significant main effect of attentional focus (p < 0:05) on mean power frequency of COP. Post-hoc showed that adopting an EFA led to a higher COP frequency of responding to balance task.
McNevin et al., 2003	To investigate if increasing the distance between body and the action effects of a focus of attention further enhances the performance advantages of an EFA. Task involved balancing on as stabilometer. Subjects were divided into four groups: one IFA and three EFA groups with different distance-to-body markers of external focus.	Results showed that all groups improved in performance. However, the two EFA groups that focused on the more distant external focus markers were more effective in maintaining their balance than the group that focused on the markers near feet or on their feet (IFA). ANOVA analysis showed a main effect of focus of attention (p<0.05). Post-hoc of EFA groups indicated differences between the EFA groups, as those with distant markers had significantly smaller RMSE than the near EFA group.
McNevin et al., 2013	To examine effects of different foci of attention on supra-postural and postural performance among different age groups.	Results of supra-postural task showed a significant main effect of focus of attention (p=0.023), with EFA yielding greater performance compared to IFA. There was also a significant effect of age (p=0.004) on supra-postural task performance, with younger adults showing better performance than older adults. For postural control, age had a significant effect on COP sway (p=0.009) and post-hoc showed that older adults had more sway compared to young adults.
Polskaia et al., 2015	To investigate if performing a continuous cognitive task would yield better performance than IFA or EFA.	Results showed a main effects of condition for COP sway area (p<0.001). Post-hoc analysis showed that the cognitive task produced significantly smaller COP sway area compared to other two conditions (IFA and EFA). No significant differences between IFA and EFA.
Richer et al., 2017a	To compare the different foci of attention to a continuous cognitive task among older adults.	Results showed a main effects of condition for COP sway area (p<0.01). Post-hoc analysis showed that the cognitive task produced significantly smaller COP sway area compared to the other two conditions (IFA and EFA). No differences were found between IFA and EFA.
Richer et al., 2017b	To investigate different foci of attention and cognitive tasks during postural control.	Results showed a main effects of condition for COP sway area (p<0.05). COP sway area was significantly smaller in EFA condition and decreased further in cognitive task condition, compared to IFA and baseline.
Rotem-Lehrer	To compare different foci of attention	Results showed that the IFA group did not show significant change

& Laufer, 2007	during the learning of a balance task among subjects following an ankle sprain injury.	over time. However, EFA group demonstrated significant differences between the pre-training and post-training postural stability scores (p<088.05).
Shea & Wulf, 1999	To compare different foci of attention when given in the form of instructions versus feedback. Four groups were recruited: 2 EFA and 2 IFA, either receiving feedback or instructions.	Results showed that the feedback groups (IFA and EFA) were more effective on the stabilometer than the instruction groups. ANOVA analysis showed that feedback and attentional focus had significant main effects on the performance (time in balance) ($p<0.05$), with feedback and EFA leading to best performance on the stabilometer.
Wulf et al., 1998	To compare an IFA versus an EFA when performing a balance motor task.	Results showed that the EFA group was significantly ($p<0.05$) better in performance than the IFA group.
Wulf et al., 2001a	To test the constrained-action hypothesis, which is put forward as an explanation for the positive effects of adopting an EFA. Task involved balancing on a stabilometer.	Results showed that there is a significant difference in RMSE between IFA group and EFA group ($p<0.01$), with the EFA group showing smaller RMSE. Results of the RT task showed that there is a significant main effect of focus of attention on RT ($p<0.01$), with the EFA group having lower RT than the IFA group.
Wulf et al., 2001b	To examine the individual differences in the preference for and effectiveness of the type of attentional focus for motor learning. Task was balancing on a stabilometer.	Participants were trained on task under both an IFA and an EFA. On retention test, participants were given the choice of which focus of attention to use. Less than 30% of participants chose an IFA, while the rest chose an EFA. The RMSE of the EFA group was significantly lower ($p<0.01$) than the IFA group.
Wulf & McNevin, 2003	To determine whether similar advantages to an EFA could be achieved by preventing subjects from focusing on their movements through the use of an attention-demanding secondary task.	Results showed that the positive effects of an EFA couldn't be reproduced by an attention-demanding secondary task. When performing the balance task, adopting an EFA produced the least amount of error compared to other groups in this study ($p<0.05$).
Wulf et al., 2003	To examine the possible effects of different attentional foci, which are promoted by a supra-postural task during a postural task (balancing on stabilometer).	Results showed that, when performing the postural task along with the supra-postural task. The EFA group had significantly smaller ($p<0.05$) RMSE compared to other groups. When performing a transfer test, by removing the source of focus of attention (supra-postural task), the EFA group continued to show significantly lesser ($p<0.05$) RMSE than other groups.
Wulf et al., 2004	To investigate the effects of different attentional foci on postural and supra-	Results showed that when adopting an EFA, there was a significant decrease ($p<0.05$) in RMSE. The improvement in balance performance

	postural tasks. Task involved standing on an unstable surface (inflated rubber disk).	could be achieved either with the EFA directed towards the postural task OR towards the supra-postural task.
Wulf et al., 2007	To examine the effects of different foci of attention on postural control while systematically varying the surface stability and limb support (double and single). Task involved standing on different stability surfaces	Results showed that there was a main effect of focus of attention on COP sway ($p<0.05$). It was found that an EFA led to lesser COP sway compared to IFA and control conditions. These findings were consistent in several balance conditions ranging in difficulty from easy to hard, such as change of support surface (hard and soft) and double and single limb support.
Wulf 2008	To compare IFA and EFA to no instruction among world-class acrobats	Participants showed similar RMSE in all conditions. ANOVA showed that the main effect of attentional focus was not significant. No differences between IFA and EFA.
Wulf et al., 2009	To investigate the generalizability of the focus of attention concept among individuals with Parkinson's disease	Results showed that COP sway was significantly less under EFA compared to other conditions (IFA and control). The main effect of attentional focus on RMSE was significant ($p<0.05$). Post-hoc analysis showed that RMSE was smaller for EFA relative to IFA and control ($p<0.05$).
Yeh et al., 2016	To investigate whether there is an age-related difference in relation to the adherence to the specific instructional constraints under EFA and IFA conditions. Authors manipulated the presence and absence of visual feedback and how that affects performance.	Results for young adults showed that during IFA conditions there was no difference between presence and absence of visual feedback. However, during EFA conditions, sway variability significantly decreased ($p<0.01$) when feedback was removed. With older adults, during IFA, presence and absence of feedback was significant, as sway variability significantly reduced ($p<0.05$) when feedback was removed. Similarly, in EFA sway variability significantly reduced ($p<0.01$) when feedback was removed.

EFA= external focus of attention; IFA= internal focus of attention; EEG= electro-encephalography; COP= center of pressure; RT= reaction time; RCT= randomized controlled trial; EMG: electromyography; RMSE= root-mean-square error; RT= reaction time.

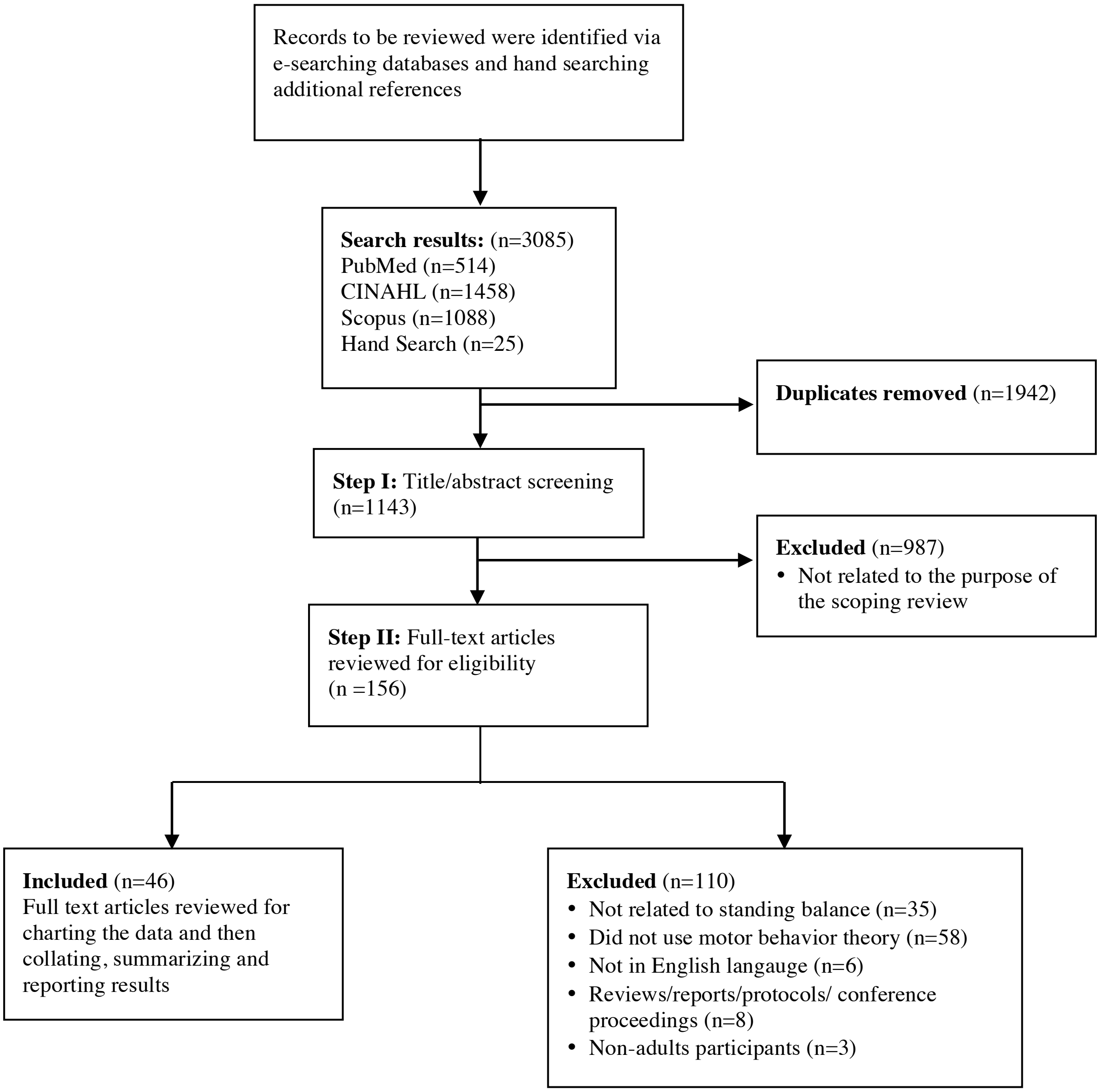

Figure 2-1. Flowchart of search and selection strategy

Appendix A

Databases Search Strategy

In our literature search we used a combination of MeSH terms and keywords to search for studies related to balance control and one (or more) of the following motor control and learning concepts: Fitts' law, focus of attention and challenge point framework. The search strategy is shown below:

1- ('Postural Balance' [MeSH] OR 'Standing Balance' [All Fields] OR 'Postural' [All Fields])

2- ('Psychomotor Performance [MeSH] OR 'Task Performance and Analysis' [MeSH] OR 'Attention' [MeSH] OR 'Neuropsychological Tests' [MeSH] OR 'Fitts law' [All Fields] OR 'Fitts' [All Fields] OR 'Speed Accuracy Tradeoff' [All Fields] OR 'Focus of Attention' [All Fields] OR 'Attentional Focus' [All Fields] OR 'Internal and External Foci of Attention' [All Fields] OR 'Extrinsic Focus' [All Fields] OR 'Intrinsic Focus' [All Fields] OR 'Challenge Point Framework' [All Fields] OR 'Challenge Point' [All Fields]

3- 1 AND 2

Appendix B

Key Articles Used for Citation Chaining

Key Articles Related to Fitts' Law:

Two key articles were used for citation chaining search for studies related to balance control and Fitts' law. The two studies are:

1. Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, 47(6), 381.
2. Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of experimental psychology*, 67(2), 103.

These two studies were chosen as they are the first studies to introduce Fitts' law as a concept. Further, they are often cited together or separately to reference Fitts' law. The first study, according to Web of Science, was cited more than 3,300 times. The second study was cited over 700 times.

Key Articles Related to Focus of Attention Theory:

Four articles related to focus of attention were used. These studies are:

1. Wulf, G., Höß, M., & Prinz, W. (1998). Instructions for motor learning: Differential effects of internal versus external focus of attention. *Journal of motor behavior*, 30(2), 169-179.
2. Wulf, G., McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology*: Section A, 54(4), 1143-1154.
3. Wulf, G., & Prinz, W. (2001). Directing attention to movement effects enhances learning: A review. *Psychonomic bulletin & review*, 8(4), 648-660.

4. Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, 6(1), 77-104.

The first study (times cited > 220) was chosen because it was the first empirical study the show the effects of different attentional foci when performing a motor task. It is often cited as the first study related to focus of attention. The second study (times cited > 330) was chosen because it was the first attempt to rationale why different foci of attention yield different motor performance. The third study (times cited > 260) was the first review of studies related to focus of attention theory. The final study (times cited > 170) was chosen because it is the latest published review of studies related to focus of attention.

Key Articles Related to Challenge Point Framework:

For the challenge point framework, only one article was used. This article, which is cited more than 400 times, was the first to put forward this framework and it is often cited when using/describing the challenge point framework. The study is:

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of motor behavior*, 36(2), 212-224.

CHAPTER 3: ANTICIPATORY POSTURAL ADJUSTMENTS DURING A FITTS' TASK: COMPARING YOUNG VERSUS OLDER ADULTS AND THE EFFECTS OF DIFFERENT FOCI OF ATTENTION

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Contributions of Authors to The Manuscript

In this study, I prepared the protocol, conducted an extensive literature search and carried out substantial equipment trials to test the experimental protocol. Feedback from Drs. Passmore, Glazebrook, Sibley and Singer regarding the study's protocol was adopted in order to enhance the study's rigor. I wrote the ethics application, recruited and screened participants and collected all the data. Working in collaboration with Drs. Passmore, Glazebrook and Singer I developed a procedure for analyzing the data. I wrote the manuscript for the study and subsequently shared it with the co-authors. All authors critically revised the draft for the manuscript for intellectual content and approved the final draft for submission. I have prepared the manuscript and it was submitted to *Human Movement Science* Journal and it was accepted for publication.

Preface

In this manuscript we build on findings obtained from the scoping review presented above. There is no previous study that examined the effects of different foci of attention on APAs. Further, no previous study examined the performance of older adults, in terms of APAs, when performing a lower extremity Fitts' task. We decided to conduct this study given the following: (1) the importance of APAs and their relation to risk of fall, especially among older adults, and (2) the potential information that can be gleaned related to balance control among older adults when performing a lower extremity Fitts' task. Therefore, the objective of this study is to investigate APAs among young and older adults when performing a lower extremity Fitts' task and the effects of different attentional foci on performance.

In this study we provide further corroboration to the beneficial effects of adopting an external focus of attention. Further, we discuss the lag in the uptake of this concept in clinical and community settings. We also provide some insights into the task used in our study and how it can differentiate between young and older adults and that it can be used as a performance-based objective measure. Finally, we interpret some of our findings within the context of the challenge point framework. The results of this study provide important information for clinicians who are involved in balance training and for researchers in the fields of motor control and learning and rehabilitation.

The following manuscript has been accepted for publication in *Human Movement Science* Journal.

Abstract

Anticipatory postural adjustments (APAs) are an integral part of standing balance. Previous research with balance control has shown that adopting an external focus of attention, compared to an internal focus of attention, yields better performance during motor skills. Despite the importance of APAs, especially among older adults, and the potential benefits of adopting an external focus of attention, studies investigating methods for improving APAs are limited. The aim of this study was to compare behavioral, kinematic and APAs measures while adopting different foci of attention among young and older adults when performing a lower extremity Fitts' task. Ten young adults (mean age 24 years ± 4.37) and ten older adults (mean age 75 years ± 5.85) performed a lower-extremity reaching task (Fitts' task) while adopting an external focus (focus on target) and an internal focus (focus on limb) in a within-subject design. A motion capture system was used to record participants' movement data. Custom software derived movement time (MT), peak velocity (PV), time to peak velocity (ttPV) and variability at target (SD_T). Electromyography (EMG) was used to determine APAs duration and magnitude. The findings showed that an external focus of attention led to significantly shorter MT, higher PV, shorter ttPV and more accuracy when reaching the target (SD_T) for both age groups. Also, EMG results showed that, with an external focus, APAs onset occurred earlier and APAs magnitude was more efficient. As predicted by Fitts' Law, participants spent more time executing movements to targets with higher indices of difficulty. Older adults compared to young adults were more adversely affected by the increase of difficulty of the Fitts' task, specifically, on measures of APAs. In conclusion, adopting an external focus of attention led to better overall movement performance when performing a lower extremity Fitts' task. The task used in the present study can distinguish between APAs for older and young adults. We recommend that

future studies expand on our findings in order to establish a performance-based objective measure of APAs to assess clinical interventions for postural control impairment.

3.1. Introduction

The focus of attention concept postulates that when performing a motor task, it is better for motor performance to direct attention towards the effects that the movement has on the environment (an external focus of attention) than directing attention to the movement itself (an internal focus of attention) (Wulf, Hößß, & Prinz, 1998). Numerous studies investigated the focus of attention concept, and it was found to be beneficial when performing and learning motor skills (Wulf, 2013; Wulf & Lewthwaite, 2016). Adopting an external focus of attention leads to improved movement efficiency and movement accuracy. Further, the benefits of adopting an external focus of attention were found to be true in different motor skills (e.g., balance, sports, fine and gross motor skills) (Lohse, Sherwood, & Healy, 2010; Marchant, Greig, & Scott, 2009; McNevin & Wulf, 2002), and different populations (e.g., non-disabled young and older adults and people with neurological impairments) (Chiviacowsky, Wulf, & Wally, 2010; Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002).

When examining the literature related to focus of attention, evidence suggests that adopting an external focus of attention yields improved performance in postural control tasks (Chiviacowsky, et al., 2010; McNevin & Wulf, 2002; Wulf, Weigelt, Poulter, & McNevin, 2003). However, no previous study related to focus of attention has examined the relation between anticipatory postural adjustments (APAs) and adopting different attentional foci. These APAs play an essential role in fall prevention, especially among individuals with balance impairments such as older adults (Aruin, 2016; de Azevedo, Claudino, Conceicao, Swarowsky, & Santos, 2016; Kanekar & Aruin, 2014a, 2014b). Yet, studies that investigate methods for improving APAs are limited (Aruin, 2016; Tisserand, Robert, Chabaud, Bonnefoy, & Cheze, 2016). Given that older adults show vulnerability in postural control and APAs (Inglin &

Woollacott, 1988; Kanekar & Aruin, 2014b; Rogers, Kukulka, & Soderberg, 1992; Woollacott & Manchester, 1993), studies that investigate methods for assessing and improving APAs among older adults are warranted. This is especially important given that impairments in APAs are linked to the risk of falling (Horak, 2006; Hyodo, et al., 2012; Kanekar & Aruin, 2014b; Muir, Berg, Chesworth, Klar, & Speechley, 2010; Uemura, Yamada, Nagai, & Ichihashi, 2011).

APAs are changes in the activity of postural muscles prior to a voluntary movement in order to maintain vertical equilibrium (Massion, 1992). Previous research suggests that an earlier onset of APAs indicates greater postural preparation in anticipation of the expected disturbance associated with voluntary movement (e.g., step initiation) (Aruin, Kanekar, Lee, & Ganesan, 2015). Further, improvement in postural control has been shown to influence the performance of reaching movements. Previous studies have shown that an improvement in APAs led to improvement in motor performance in terms of accuracy, movement time, and peak velocity (Saito, Kominami, Yamanaka, Takeda, & Fukushima, 2011; Saito, Yamanaka, Kasahara, & Fukushima, 2014). As such, improvement in kinematic and behavioral measures is associated with overall better postural control.

A few studies have investigated APAs during a lower extremity Fitts' task, and reported that APAs are predictable when participants performed a Fitts' task (Bertucco & Cesari, 2010; Bertucco, Cesari, & Latash, 2013; Danion, Duarte, & Grosjean, 1999; Duarte & Freitas, 2005; Duarte & Latash, 2007). The use Fitts' law is advantageous as it is resistant to learning and has varying difficulty levels (Schmidt & Lee, 2011). Since the introduction of this law, several studies have shown the robustness of Fitts' law and its applicability to different movement types (Plamondon & Alimi, 1997). The formal linear relationship of Fitts' law is $MT = a + b \log 2 (2A/W)$, where MT is movement time, a and b are empirical constants, A and W are amplitude of movement and width of target, respectively. The logarithmic function of this formula is called the index of difficulty (ID), ID= log2 (2A/W), and is measured in bits (Fitts, 1954; Fitts & Peterson, 1964). In other words, Fitts' law can be described as a relationship between MT and task difficulty; when aiming for a target, MT increases with task difficulty.

Studies that looked into APAs during a lower extremity Fitts' task have only investigated participants who were young, non-disabled adults. To our knowledge there are no previous studies related to APAs during a Fitts' task among individuals in several age groups. On the other hand, studies that looked into APAs among older adults indicate that APAs are significantly delayed and lower in amplitude among older adults compared to young adults (Inglin & Woollacott, 1988; Kanekar & Aruin, 2014b; Rogers, et al., 1992; Woollacott & Manchester, 1993). Further, studies that investigated Fitts' law tasks among older adults report that Fitts' law holds; however, older adults performed significantly slower than younger participants, and showed more variability in performance (Passmore, Burke, & Lyons, 2007; Sleimen-Malkoun, Temprado, & Berton, 2013). Additionally, as mentioned above no previous study has investigated the effects of different foci of attention on APAs. Investigating APAs within the context of focus of attention and Fitts' law may lead to identifying methods for assessing and improving APAs among older adults.

3.1.1. Aims and Hypotheses

The primary aim of this study was to investigate the effects of different foci of attention on APAs parameters (measured as electromyography [EMG] duration and magnitude) during a lower extremity Fitts' task among young and older adults. The secondary aims include: (1) to compare the differences in movement time (MT) between young and older adults during a lower extremity Fitts' task with different attentional foci; and (2) to compare the kinematic variables of movements to varying targets (peak velocity [PV], time to peak velocity [ttPV] and variability at target endpoint [SD_T]) between young and older adults with different attentional foci.

Based on previous studies, we hypothesized that when adopting an external focus of attention participants would show earlier APAs onset and more efficient (lower) APAs magnitude. Further, we anticipate that when adopting an external focus of attention the improvement in APAs is accompanied with improved performance in behavioral and kinematic measures. This improved performance is seen as shorter MT, higher PV, shorter ttPV and more accurate target endpoint (SD_T).

3.2. Methods

3.2.1. Participants

Ten older adults (65 years or older) and ten young adults (18-40 years) were recruited for this study. Footedness was assessed using the Waterloo Footedness Questionnaire-Revised (WFQ-R) (Elias, Bryden, & Bulman-Fleming, 1998). The WFQ -R includes thirteen questions that are answered on a 5-level Likert-type scale to determine whether the right foot or left foot is the most often used. Responses were assigned a value between -2 and 2, with scores closer to 0 reflect equal foot preference, score closer to -2 indicate left foot preference, and 2 right foot preference (Elias, et al., 1998). An a priori power calculation ($\beta= 0.8$, $\alpha=0.05$) with published data for APAs onset time during Fitts' law tasks determined a sample size of 9 participants per group was sufficient. All participants in our study provided an informed consent prior to data collection. The Health Research Ethics Board at the University of Manitoba approved all procedures.

3.2.2. Inclusion and Exclusion Criteria

All participants had to answer 'no' to all questions in the PAR-Q (Thomas, Reading, & Shephard, 1992). The Physical Activity Readiness Questionnaire (PAR-Q) was used ensure that participants do not have medical problems that might negatively impact them after participation in this study. All participants were required to score above '53' on Berg balance scale or would not be eligible to participate in the study (Berg, Wood-Dauphine, Williams, & Gayton, 1989). This score –53– on the Berg balance scale was chosen as a cut-off as previous research suggests that older adults with this score and higher were more likely to have greater balance ability and functional independence (Berg, Maki, Williams, Holliday, & Wood-Dauphinee, 1992; Berg, Wood-Dauphinee, Williams, & Maki, 1992; Steffen, Hacker, & Mollinger, 2002). The need to define a minimum score on the Berg balance scale was determined as the task in this study requires participants to stand independently and perform a lower extremity task with one foot, while supporting weight on the other lower extremity. One consistent author (SA), who is experienced with the above tests, always administered the previous measures. After the previous information was collected, and the participants met the criteria, a session for the experiment was scheduled.

3.2.3. Apparatus

The instruments that were used in this study included an optoelectronic motion capture system and an EMG system. The motion capture system used for this study was the Optotrak 3D-investigator (Northern Digital Inc. [NDI], Canada). This system records the 3-dimensional displacement of infrared-emitting diode markers. The movement kinematics of two markers was recorded using this system. These two markers were placed bilaterally on the distal aspect of the great toe. Data were collected at 200 Hz.

The EMG system used for this study was the Power 1401 data acquisition system, the 1902 amplifier with a 4-channel electrode adaptor box and the software 'Signal' (Cambridge Electronic Design [CED], UK). This EMG system uses snap connection leads to attach to disposable pre-gelled Ag/AgCl, bipolar electrodes that mount directly to the skin with an adhesive pad. The EMG signal was sampled at 2000 Hz. Muscle activity of the soleus and tibialis anterior muscles were recorded. These muscles were chosen because they are part of the main lower extremity postural muscles and can provide an overall representation of APAs (Nashner, 1977). The above muscles in the stance and moving limbs were recorded. Electrode placement for the EMG was done in accordance with Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens, et al., 2000; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The Optotrak and EMG systems were synchronized during data collection using a trigger pulse and linked to their respective software and computer.

3.2.4. Procedure

The protocol for this study involved participants standing with bare feet on a level surface with their feet shoulder-width apart and their arms at their sides. Participants were asked to align the distal tips of both great toes to a straight line shown on the floor in front of them (i.e., the starting position). An adjustable walker was placed in front of participants, and to this walker, a digital projector was mounted to project 30-inch images on the floor. Each participant was instructed to point with the tip of the great toe to a square target on the floor displayed by the projector. Targets had a predefined width (W) and were located at a predefined amplitude (A). Target position was anterior to the participant, in the sagittal plane. The task in this study involved a single discrete movement to the target. The instructions given to each subject prior to a block of trials was a typical Fitts' task instruction: "be as fast and as accurate as possible in your pointing movement." Participants were also asked to hold the position of the foot after completing the task until the end of trial in order to ensure proper data collection.

Each trial lasted 10 seconds and it started with the participant standing in the starting position. The image for the block of trials was presented to the participant. A 'go' auditory signal from the computer system indicated that participants should initiate the movement towards the target. Three movement amplitudes (A=20, 40 and 60 cm) and three target widths (W=2.5, 5 and 10 cm) were used in this study. The combinations of these amplitudes and widths yield 9 different conditions with an ID ranging from 2.00 to 5.58 bits (Figure 3-1). The amplitude was measured from the center of the target to the line of the starting position. The nine combinations were presented in a random order, with each combination presented six times. Participants were given practice trials (1-3) prior to each condition. Once completed, the procedure was repeated with the opposite foot (108 trials).

Each participant underwent the previous procedure twice (216 trials total) in order to investigate the effects of adopting different types of attentional foci. This was done by giving participants additional instructions during trials to manipulate focus of attention. During the internal focus of attention condition, participants were told to "focus on your foot; concentrate on your foot's motion when you reach forward with your foot." During the external focus condition, participants were told to "focus on the target; concentrate on the middle of the target." Participants had to perform the previous experiment under both foci of attention conditions. To rule out order effects, half of the participants performed the experiment under the internal focus condition followed by the external focus condition, while the other half of participants started with the external focus condition followed by the internal focus condition. Instruction reminders (for Fitts' task and focus of attention) were provided to participants prior to each Fitts' task condition. It was anticipated that each participant would perform the experiment in one session and within two hours. Between conditions participants were asked to rest or walk around, as they preferred, in order to minimize attentional and physical fatigue.

3.2.5. Data processing and analyses

3.2.5.1. Data processing. Data processing was done using a custom computer software developed using Matlab (release 2014b, The Mathworks Inc., USA). For kinematic data, only sagittal plane data were analyzed, as this was the main plane of movement. Position data were low-pass filtered at 10 Hz. Peak velocity (PV), measured in millimeter/second (mm/s), and time to peak velocity (ttPV), measured in millisecond (ms), were determined from the velocity profile in the sagittal plane of the marker on the great toe of the pointing foot. We defined PV as the greatest velocity attained in the sagittal plane of movement by the great toe. The ttPV definition was the time following movement onset to reach peak velocity (ms). Movement onset (T_0) was defined as the first frame when velocity in the primary axis of movement reached 35 mm/s during a particular trial. Movement end time (T_{END}) was defined as the frame where after T_0 when velocity in the primary axis of movement fell below 35 mm/s and remained below for at least 100ms. Movement time (MT) was defined as the time between T_0 and T_{END}. Variability at target (SD_T) was estimated in the primary axis of movement using the standard deviation of the movement endpoints relative to the center of the target.

For EMG data, the raw signals were first band-pass filtered (40-500 Hz), then full-wave rectified and then low-pass filtered at 10 Hz. A zero-lag, 4th order Butterworth filter was used for processing. Subsequently, onset of EMG activity (T_{0_EMG}) was determined. This was done by detecting the first increase above 2 *SDs* from EMG baseline. Baseline level was defined as the mean EMG activity between 100 and 400ms of data recording. The net time between T_{0_EMG} and T_0 was defined as APA duration (APA_D).

To quantify APA magnitude (APA_M), we performed the following procedure. First, the integral of EMG activity from 100 ms to 400 ms was determined ($Integ_{100-400}$). Second, the integral of EMG activity from T_{0_EMG} to T_0 was determined ($Integ_{T0EMG-T0}$). Finally, the APA_M measure was defined as the following ratio:

$APA_M = (Integ_{T0EMG-T0} - Integ_{EMG100-400}) / Integ_{EMG100-400}$ (Figure 3-2).

The EMG data for both limbs during both conditions (stance and moving) were processed to obtain APA_D and APA_M.

3.2.5.2. Dependent variables and statistical analyses. The dependent variables were: MT, PV, ttPV, SD_T, APA duration (APA_D) and APA magnitude (APA_M). For all dependent variables separate: 2 age groups x 2 foci of attention x 3 amplitudes x 3 target widths, mixed model analyses of variance (ANOVA) with repeated measures were conducted. Measures of APAs (duration and magnitude) were collapsed for both right and left legs and were separated as stance and moving. Age group was a between-subject factor and the remaining were within-subject factors. We tested for simple effects on interactions and we have adjusted alpha (α) for post-hoc tests. Post-hoc analyses were performed using Tukey's HSD procedure. The significance level for all statistical analyses was set to $\alpha=0.05$. A preliminary analysis was performed to confirm that order didn’t interact with attentional focus. The analysis involved comparing participants who started with an internal focus against those who started with an external focus across the same population (i.e., older adults and young adults). Statistical analyses were performed using SPSS statistical package software. Only significant effects are reported in the results below.

3.3. Results

Twenty participants were recruited, ten older adults and ten young adults. The session time required to complete the experiment was 1.5-2.5 hours (mean=2.13). Three females and seven males from each age group were recruited. The mean age for young adults was 24 years (±4.37) and mean age for older adults was 75 years (±5.85). Results of the WFQ-R showed that participants were predominantly right-footed. All participants had a score of above 54 on the Berg balance scale. Summary of participants' characteristics is shown in Table 3-1.

3.3.1. Behavioral and Kinematic Measures

3.3.1.1. Movement Time. MT was significantly lower with an external focus of attention compared to an internal focus, $F(1,18) = 62.9$, $p<0.001$, $\eta_p^2=0.78$. Older adults had longer MT compared to young adults, $F(1, 18) = 12.5$, $p=0.002$, $\eta_p^2=0.41$ (Figure 3-3.a). In addition, higher amplitude resulted in longer MT, $F(2, 36) = 146.7$, $p<0.001$, $\eta_p^2=0.89$. Smaller width resulted in longer MT $F(2, 36) = 12.5$, $p<0.001$, $\eta_p^2=0.41$ (Figure 3-3.b). Significant interactions were found for focus of attention by amplitude $F(2, 36) = 8.5$, $p<0.001$, $\eta_p^2=0.32$, and focus of attention by age group $F(1, 18) = 4.6$, $p<0.05$, $\eta_p^2=0.21$. Post hoc analyses showed that all amplitudes resulted in different MTs, $p<0.001$; and only widths 2.5 and 10cm resulted in significantly different MT, $p<0.05$. All other comparisons were not significant.

3.3.1.2. Peak Velocity. PV was significantly higher with an external focus of attention compared to an internal focus, $F(1,18) = 46.2$, $p<0.001$, $\eta_p^2=0.72$ (Figure 3-4.a). Results also showed that as amplitude increased PV increased, $F(2, 36) = 202.1$, $p<0.001$, $\eta_p^2=0.92$. Also, as width increased PV increased, $F(2, 36) = 127.3$ $p<0.001$, $\eta_p^2=0.88$ (Figure 3-4.b). Post hoc analysis showed that all amplitudes and widths resulted in different PV, $p<0.001$. No significant differences were found between age groups. All other comparisons were not significant.

3.3.1.3. Time to Peak Velocity. Results showed that ttPV was significantly shorter with an external focus compared to an internal focus, $F(1,18) = 27.8$, $p<0.001$, $\eta_p^2=0.61$ (Figure 3-5.a). In addition, higher amplitude resulted in longer ttPV, $F(2, 36) = 113.9$ $p<0.001$, $\eta_p^2=0.86$ (Figure 3-5.b). Smaller width resulted in longer ttPV, $F(2, 36) = 18.9$ $p<0.001$, $\eta_p^2=0.51$. Post hoc analysis indicated that all amplitudes and widths resulted in different ttPV, $p<0.01$. No significant differences were found between age groups. All other comparisons were not significant.

3.3.1.4. Variability at Target. SD_T was significantly smaller with an external focus of attention compared to an internal focus, $F(1,18) = 332.0$, $p<0.001$, $\eta_p^2=0.95$ (Figure 3-6.a). Results also showed that shorter amplitude led to smaller SD_T, $F(2, 36) = 3.8$, $p<0.05$, $\eta_p^2=0.17$. Larger width resulted in smaller SD_T, $F(2, 36) = 10.9$, $p<0.001$, $\eta_p^2=0.38$ (Figure 3-6.b). Significant interactions were found for focus of attention by amplitude $F(2, 36) = 3.5$, $p<0.05$, $\eta_p^2=0.16$, and focus of attention by width $F(2, 36) = 9.7$, $p<0.001$, $\eta_p^2=0.35$. Post hoc analysis showed that 20 and 60cm amplitudes resulted in significantly different SD_T ($p<0.001$). Similarly, widths 2.5 and 10 resulted in significantly different SD_T ($p=0.026$). Overall, an external focus of attention led to smaller SD_T, shorter amplitude led to smaller SD_T but only for external focus, bigger width led to smaller SD_T (only for external focus). No significant differences were found between age groups. All other comparisons were not significant.

3.3.2. Anticipatory Postural Adjustments Measures

3.3.2.1. Anticipatory Postural Adjustments Duration. Results showed that adopting an external focus of attention led to earlier onset of APAs for both muscles, tibialis anterior (TA) and soleus (SO) during both conditions, moving and stance, TA moving: $F(1,18) = 91.6$, $p<0.001$, $\eta_p^2=0.84$, TA stance: $F(1,18) = 126.1$, $p<0.001$, $\eta_p^2=0.88$, SO moving: $F(1,18) = 130.6$,

$p<0.001$, $\eta_p^2=0.88$, and SO stance: $F(1,18) = 180.8$, $p<0.001$, $\eta_p^2=0.91$. Results also showed that young adults exhibited earlier APAs onset compared to older adults for TA stance $F(1, 18) = 8.3$, $p<0.01$, $\eta_p^2=0.32$, and SO stance $F(1, 18) = 4.9$, $p=0.04$, $\eta_p^2=0.21$ (Figure 3-7.a). Significant interactions were found for focus of attention by age group for TA stance $F(1, 18) = 7.2$, $p=0.01$, $\eta_p^2=0.29$ and SO stance $F(1, 18) = 6.2$, $p=0.02$, $\eta_p^2=0.27$. A significant interaction was found for focus of attention by amplitude by age group for SO stance $F(2, 36) = 7.3$, $p<0.01$, $\eta_p^2=0.29$. For both age groups, as amplitude increased APAs onset occurred earlier but this was only seen with external focus and for the stance soleus muscle (Figure 3-7.b). No significant effects were found for width on APA_D. All other comparisons were not significant.

3.3.2.2. Anticipatory Postural Adjustments Magnitude. APA_M was significantly smaller with an external focus of attention compared to an internal focus for both TA and SO during both moving and stance conditions, TA moving: $F(1,18) = 11.6$, $p<0.01$, $\eta_p^2=0.39$, TA stance: $F(1,18) = 12.7$, $p<0.01$, $\eta_p^2=0.41$, SO moving: $F(1,18) = 29.7$, $p<0.01$, $\eta_p^2=0.62$, and SO stance: $F(1,18) = 53.9$, $p<0.001$, $\eta_p^2=0.75$. Results also showed that young adults exhibited larger APA_M compared to older adults for SO moving, $F(1, 18) = 20.5$, $p<0.001$, $\eta_p^2=0.53$, and SO stance, $F(1, 18) = 31.9$, $p<0.001$, $\eta_p^2=0.64$ (Figure 3-8.a). Increased amplitude led to larger APA_M for TA moving, $F(2, 36) = 4.7$, $p<0.05$, $\eta_p^2=0.21$, and TA stance, $F(2, 36) = 4.2$, $p<0.05$, $\eta_p^2=0.19$ (Figure 3-8.b). Significant interactions were found for focus of attention by age group for SO stance $F(1, 18) = 13.7$, $p<0.01$, $\eta_p^2=0.43$. A significant interaction was found for focus of attention by amplitude for TA moving $F(2, 36) =3.3$, $p<0.05$, $\eta_p^2=0.15$. No significant effects were found for width on APA_M. All other comparisons were not significant.

3.4. Discussion

This study investigated APAs and other movement parameters among young and older adults when performing a lower extremity Fitts' task and adopting different foci of attention. We conducted the present study in order to assess if the reported positive effects of adopting an external focus of attention extend to APAs among both older and young adults when performing a lower extremity Fitts' task. Due to the importance of APAs in fall prevention, it is imperative to investigate methods for improving them. This is especially important given that older adults show impairments in APAs, which have been linked to the risk of falling (Horak, 2006; Hyodo, et al., 2012; Kanekar & Aruin, 2014b; Muir, et al., 2010; Uemura, et al., 2011).

Both age groups in this study benefited from adopting an external focus of attention when performing the Fitts' task. The beneficial effect of adopting an external focus was evident in the shorter movement times, larger peaks of velocity, shorter times to peak velocity and the more accurate target endpoints. Further, the benefits of adopting an external focus were evident in measures of APAs, as APAs occurred earlier with an external focus and magnitude of APAs was lower and more efficient. The beneficial effects of adopting an external focus of attention were shown repeatedly across multiple experimental studies (Wulf, 2013; Wulf & Lewthwaite, 2016). These beneficial effects ranged from movement effectiveness (e.g., maintaining balance, reaching accuracy) to movement efficiency (e.g., muscular activity, force production, speed). Wulf and colleagues proposed the constrained action hypothesis as a testable explanation for the effects of different foci of attention (Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001). According to this view adopting an internal focus promotes conscious control of movement, which leads individuals to constrain their motor system by interfering with automatic control processes. Conversely, an external focus induces an automatic mode of control by using unconscious, fast, and reflex-like control processes. Several experimental studies support this hypothesis and provide evidence related to changes in attentional capacity, movement-adjustments frequency and reduced reaction time detected under different attentional foci (Kal, van der Kamp, & Houdijk, 2013; Lohse, 2012; McNevin, Shea, & Wulf, 2003; Wulf, McNevin, et al., 2001; Wulf, Shea, et al., 2001).

The results of our study show that target amplitude had a more prominent effect on outcome measures than the width of the target. This finding is seen in the higher effect size of amplitude in behavioral and kinematic measures and the lack of a significant effect of width on measures of APAs. It was possible that participants adjusted their movement planning primarily based on movement amplitude. This finding was supported by the fact that there was no effect of target width on variability at movement endpoint when participants were adopting an internal focus. However, when movement planning was managed under an external focus of attention, target width had a significant effect on variability at target. This finding also supports the constrained action hypothesis mentioned above. When participants were consciously controlling their movements they perceived the difficulty of the task based on movement amplitude. However, when adopting an external focus, movement planning was more automatic and thus all variables of difficulty affected performance. This finding was similar to previous studies that also reported a more prominent effect of movement amplitude rather than target width (Bertucco & Cesari, 2010; Duarte & Latash, 2007; Passmore, et al., 2015).

The older population in our study showed significant differences in outcome measures compared to young adults. This finding was similar to previous studies that utilized similar outcome measures (Inglin & Woollacott, 1988; Kanekar & Aruin, 2014a; Passmore, et al., 2007; Rogers, et al., 1992; Sleimen-Malkoun, et al., 2013; Woollacott & Manchester, 1993). This finding supports the general slowing hypothesis (GSH) among older adults. The GSH suggests that slowing is not exclusive to the cognitive domain, but extends to the motor domain (Sleimen-Malkoun, et al., 2013). Nonetheless, there were no differences in peak velocity and time to peak velocity between the age groups. The equivalency between age groups in peak velocity and time to peak velocity does not necessarily mean age groups were similar in overall performance. Older adults during a Fitts' law task tend to show more movement adjustments (i.e., shifting between acceleration to deceleration) and do not perform the task similarly to young adults (Goggin & Meeuwsen, 1992; Sleimen-Malkoun, et al., 2013).

Our results showed that the two age groups and amplitude had an effect on onset of APAs. However, this effect was only observed when the leg was in stance position and not while moving. When performing the Fitts' task, individuals in our study shifted from a bipedal to a unipedal stance. Therefore, the stance leg was responsible for maintaining equilibrium while performing the task. Given the above results, it is reasonable to suggest that the aforementioned parameters (i.e., age group and amplitude) affected the stance leg more than the swing leg. Further, previous studies related to APAs also reported that duration of APAs, as measured by EMG, of the stance leg was more affected by the study parameters such as movement amplitude (Bertucco & Cesari, 2010; Ito, Azuma, & Yamashita, 2003; Yiou, Caderby, & Hussein, 2012).

For APA magnitude, the results showed that movement amplitude only affected the TA muscles, while differences between age groups were only seen in the SO muscles. These findings suggest that, during movement planning, the difficulty of the task was interpreted by the amplitude of movement and the load was carried out primarily by the TA muscles. Further, our findings suggest that the TA muscles were not affected by the different age groups as only the SO muscles were affected. The above findings are consistent with previous research, which indicates that TA muscle strength only shows difference between age groups after the age of 80 years (McNeil, Doherty, Stashuk, & Rice, 2005). Given that the mean age for the older group was 75y, it is expected that the age group did not affect the TA muscles.

The overall findings of our study can be interpreted within the context of the challenge point framework (Guadagnoli & Lee, 2004). The challenge point framework relates the variables of a task to the skill level of the performer, the difficulty of the task and the information related to the motor skill. Guadagnoli and Lee (2004) state that as the difficulty of a motor task increases, the overall performance decreases depending on the ability of the performer. However, the authors suggest that in order to achieve maximum performance of a motor skill, there is an "optimal challenge point" in the degree of task difficulty and availability of information, which leads to optimal performance of motor skills. At this optimal challenge point the individual is optimally challenged with the task difficulty relative to their skill level, and then efficient performance and learning of a motor skill can occur.

In our study, the findings suggest that the optimal challenge point for a task similar to our study is different between older and young adults. The difference in the optimal challenge point between the two age groups can be seen in their differences in movement planning as assessed by the duration of APAs. In other words, as amplitude increased (i.e., difficulty increased) the differences between the two groups became more pronounced. Therefore, when assessing APAs among older adults using longer amplitudes would be more indicative of APAs impairments than smaller movement amplitudes. Another interesting finding in our study was that adopting an external focus of attention seemed to alter the optimal challenge point. This alteration of the optimal challenge point can be seen in the target endpoint variability. When participants adopted an internal focus their target endpoint variability was similar for amplitudes 40 cm and 60 cm.

However, when adopting an external focus of attention a difference was present between the two aforementioned amplitudes. This difference suggests that an external focus of attention helps distinguish between the different levels of difficulty and thus promote performance by adequately identifying the optimal challenge point for the performer.

The findings in our study have important clinical implications. Adopting an external focus of attention appears to promote beneficial effects for both young and older adults. The beneficial effects can be seen in the behavioral and kinematic measures of the study as adopting an external focus led to shorter movement time and time to peak velocity, higher peak velocity, more endpoint accuracy. Previous studies suggest that an improvement in behavioral and kinematic measures is associated with overall better postural control (Saito, et al., 2011; Saito, et al., 2014). Further, these benefits were seen with APAs measures as adopting an external focus led to earlier activation of APAs and decreased muscle activation. These findings were similar to previous studies that investigated focus of attention and indicated that adopting an external focus led to improved movement accuracy and efficiency (Wulf, 2013; Wulf & Lewthwaite, 2016). Although studies of attentional foci in motor behavior had shown the benefit of adopting an external focus, clinical and community uptake has lagged behind. Several studies had shown that during training of motor skills, clinical practitioners provide learners with statements that promote an internal focus of attention (Durham, Van Vliet, Badger, & Sackley, 2009; Johnson, Burridge, & Demain, 2013; Porter, Wu, & Partridge, 2010). The previous studies suggest that there is a need to promote the utilization of an external focus of attention during motor training.

The findings in our study also provide the groundwork for determining the challenge point at which older adults are at a higher risk of falling and thus in need of clinical intervention. As mentioned above, APAs impairment is linked to risk of falling (Horak, 2006; Hyodo, et al., 2012; Muir, et al., 2010; Uemura, et al., 2011). The task used in our study can be used as a performance-based objective outcome measure of APAs. By utilizing higher movement amplitudes, APAs parameters show more pronounced differences between young and older adults. Further, by establishing a point at which older adults are at higher risk of falling, the task in our study can serve as a useful tool for rehabilitation clinicians.

3.5. Conclusion

The present study showed that adopting an external focus of attention yields beneficial effects for both older and younger adults when performing a lower extremity Fitts' task. Furthermore, the task distinguished between young and older adults in terms of behavioral, kinematic and APAs measures. Movement amplitude had the greatest effect on performance for both age groups. Finally, the results found in our study should be extended in order to investigate a cut-off point at which APAs are impaired and are in need of clinical intervention.

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Table 3-1. Participants' Characteristics

Demographics	Older Adults	Young Adults
N (males/females)	10 (7/3)	10 (7/3)
Age (mean ± SD)	75 years ± 5.85	24 years ± 4.37
Height (mean ± SD)	175.6 cm ± 6.57	174.3 cm ± 5.86
WFQ-R[*] score (median)	5.5	9
Berg balance scale[†] score (median)	54	56

SD: Standard deviation; WFQ-R: Waterloo Footedness Questionnaire-Revised.

[*] The WFQ-R includes thirteen questions that are answered on a 5-level Likert-type scale to determine whether the right foot or left foot is the most often used. Responses are assigned a value between -2 and 2. The total score can be used to determine footedness, with a score of -7 or less considered left-footed, a score of -6 to +6 considered mixed-footed, and a score of +7 or higher considered right-footed.

[†] Berg balance scale is a 14-item observational rating scale that provides a measure of functional balance and has an overall score of 56.

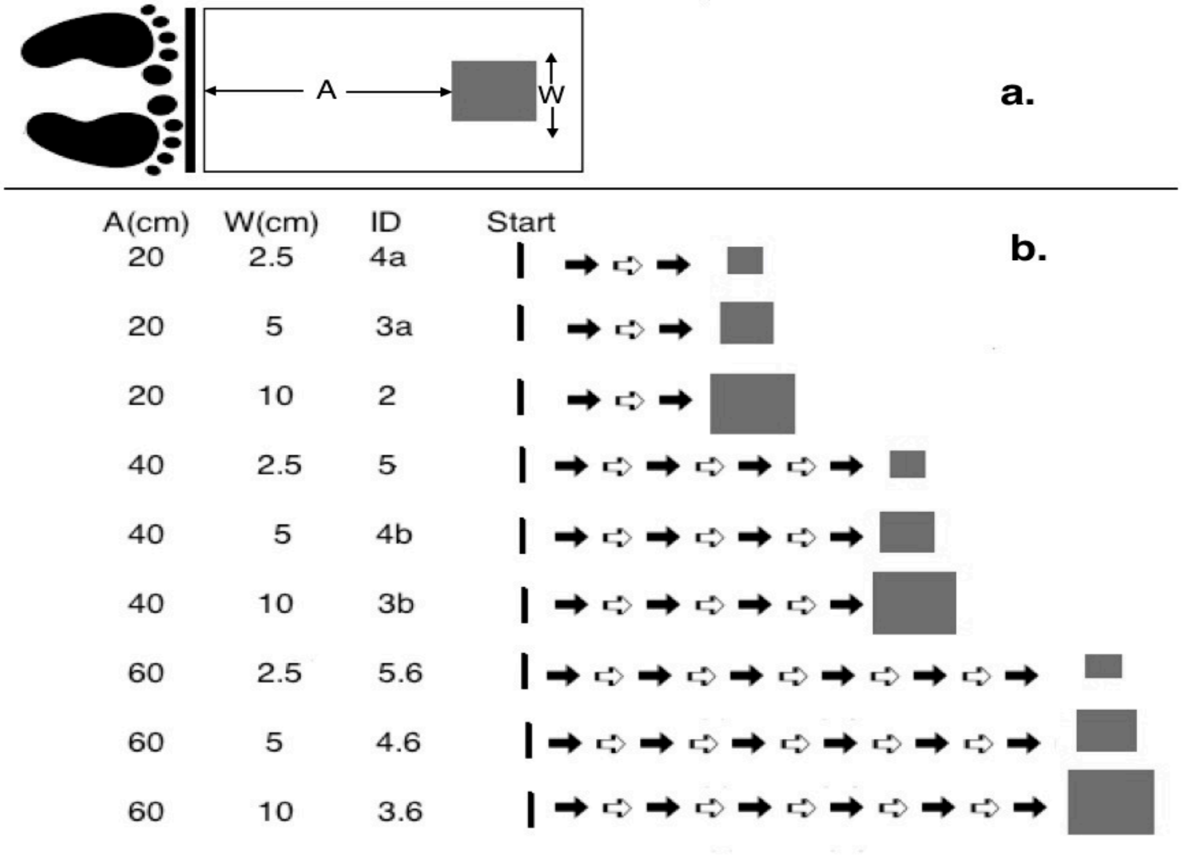

Figure 3-1. Experimental setup. Figure 3-1.a. shows the starting position for performing the task. Figure 3-1.b. shows the nine combinations of movement amplitude and target width with the resultant index of difficulty. A=amplitude, W=width, ID=index of difficulty.

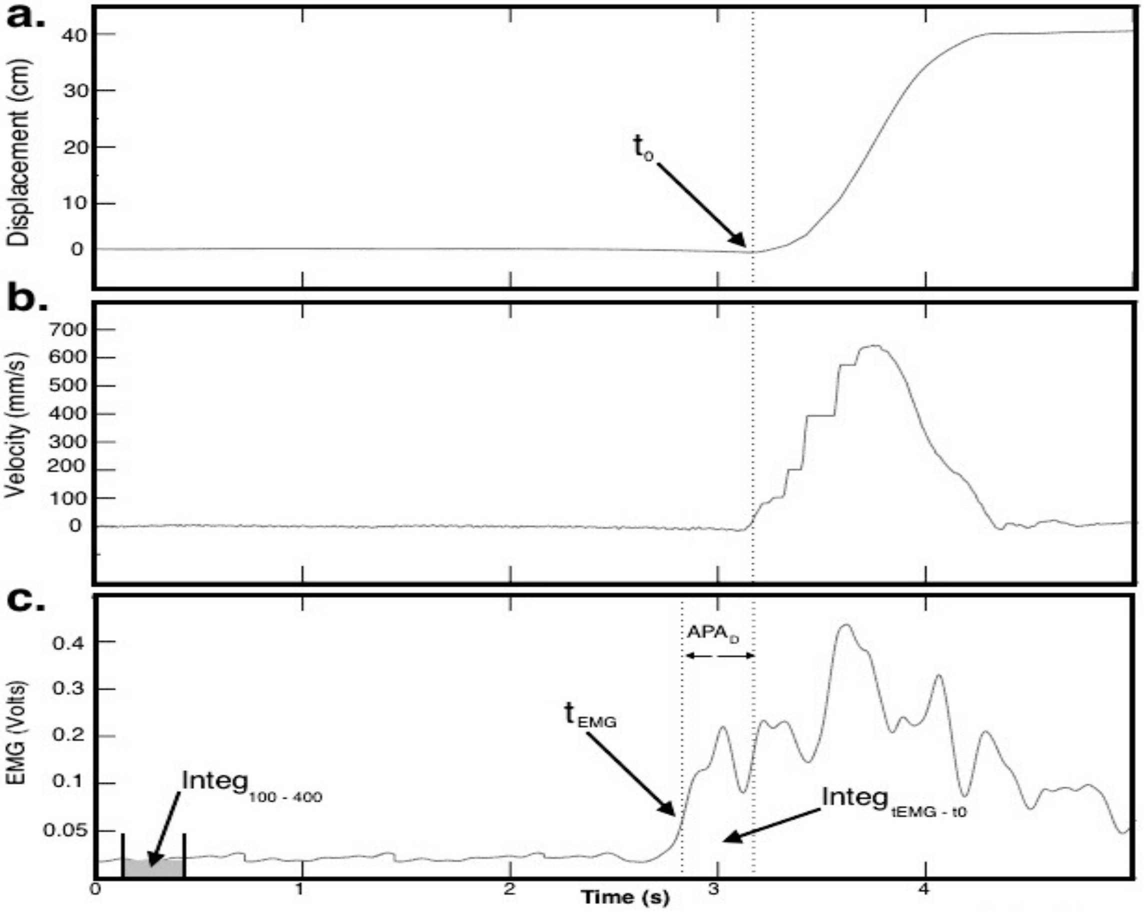

Figure 3-2. Example of a movement trial (older adult). Displacement and velocity profiles of the moving leg are shown in 3-2.a and 3-2.b. Movement onset is labeled as t_0. Figure 3-2.c shows the EMG profile for the soleus muscle of the stance leg. Beginning of EMG activity is labeled as t_{EMG} and the duration between t_{EMG} and t_0 is the duration of anticipatory postural adjustment (APA_D). The integral of EMG activity within APA_D was determined ($\text{Integ}_{tEMG\text{-}t0}$). Also, the integral of EMG between 100 to 400 ms was determined ($\text{Integ}_{100\text{-}400}$). Using $\text{Integ}_{tEMG\text{-}t0}$ and $\text{Integ}_{100\text{-}400}$ magnitude of anticipatory postural adjustment was determined.

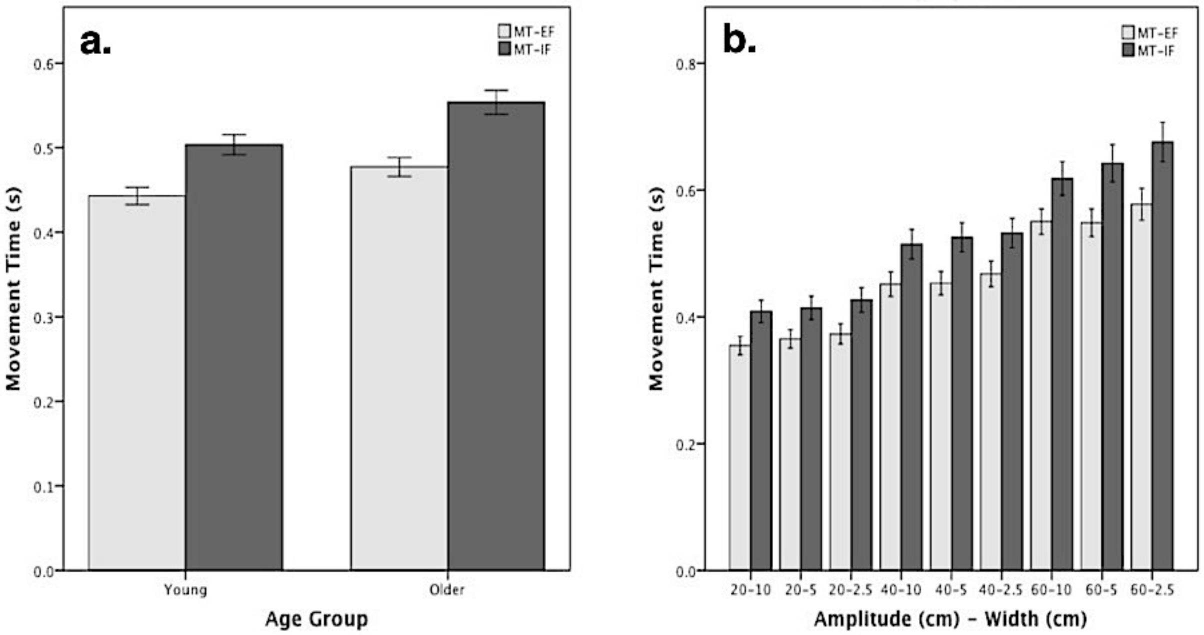

Figure 3-3. Mean movement time (MT) as a function of age group and amplitude - width. Figure 3-3.a. shows the difference in MT between young and older adults. Figure 3-3.b. shows MT plotted against the different combinations of movement amplitude and width. Error bars reflect standard error of the mean.

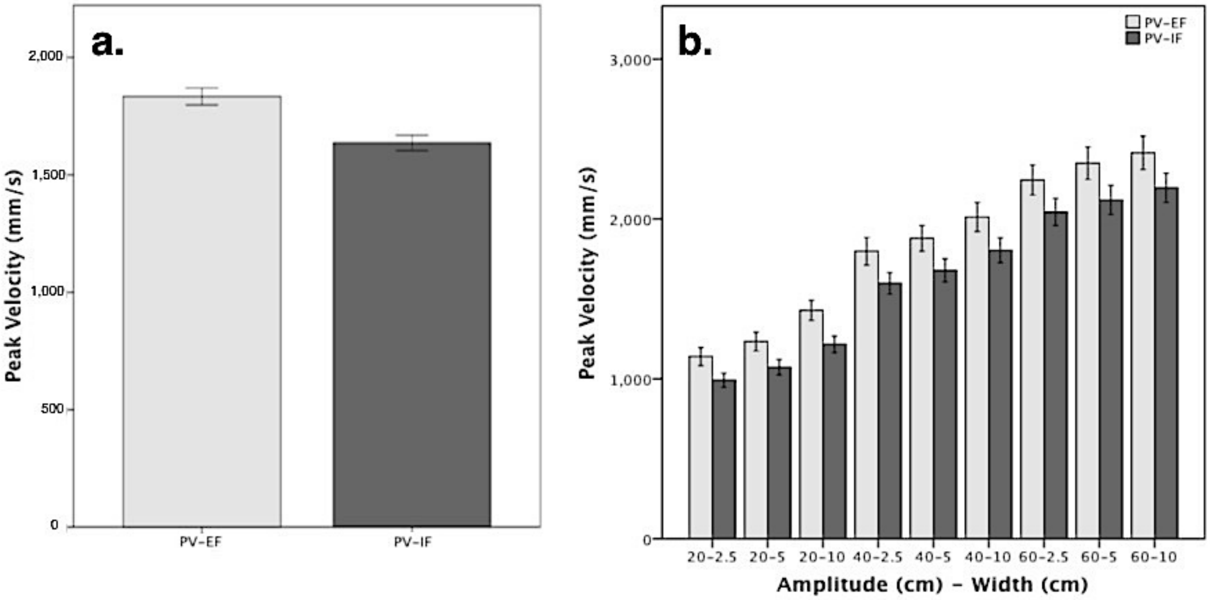

Figure 3-4. Mean peak velocity (PV) as a function of attentional foci and amplitude - width. Figure 3-4.a. shows the difference in PV when focusing externally (PV-EF) and when focusing internally (PV-IF). Figure 3-4.b. shows PV plotted against the different combinations of movement amplitude and width. Error bars reflect standard error of the mean.

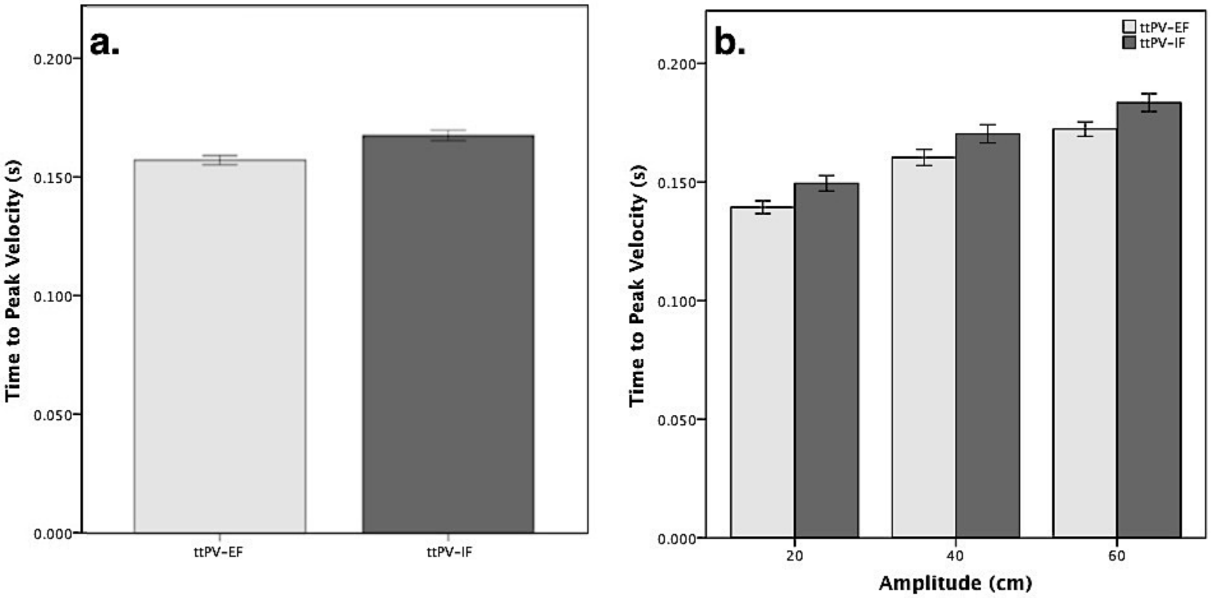

Figure 3-5. Mean time to peak velocity (ttPV) as a function of attentional foci and amplitude. Figure 3-5.a. shows the difference in ttPV when focusing externally (ttPV-EF) and when focusing internally (ttPV-IF). Figure 3-5.b. shows ttPV plotted against the different movement amplitudes. Error bars reflect standard error of the mean.

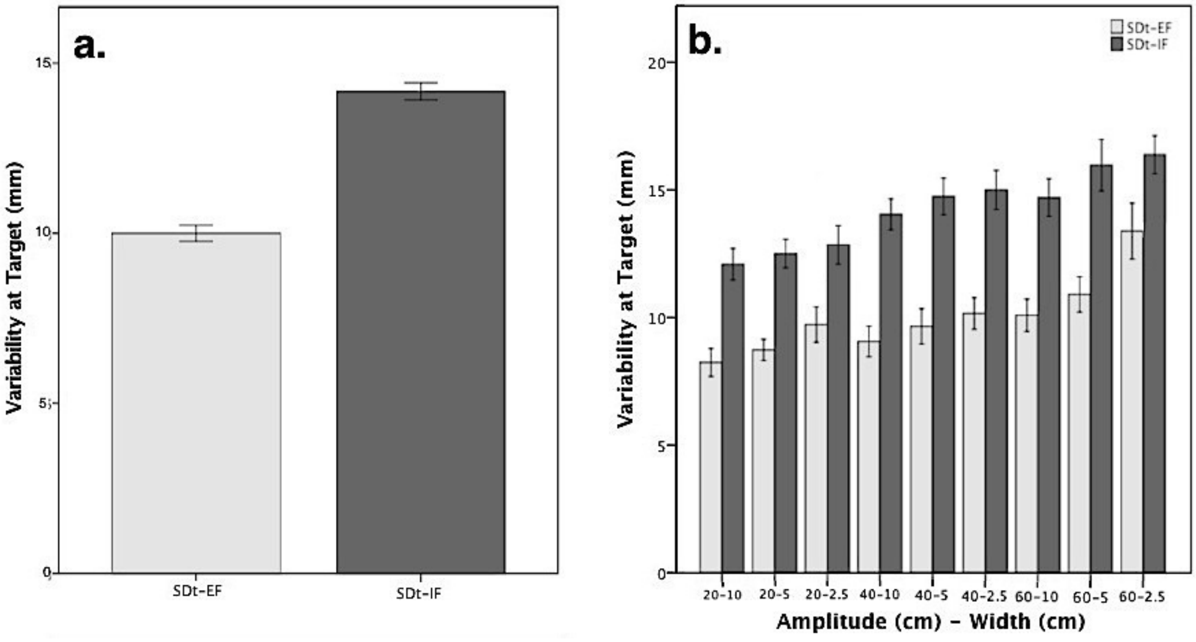

Figure 3-6. Mean variability at target (SDt) as a function of attentional foci and amplitude - width. Figure 3-6.a. shows the difference in SDt when focusing externally (SDt-EF) and when focusing internally (SDt-IF). Figure 3-6.b. shows SDt for internal and external focus plotted against the different combinations of movement amplitude and width. Error bars reflect standard error of the mean.

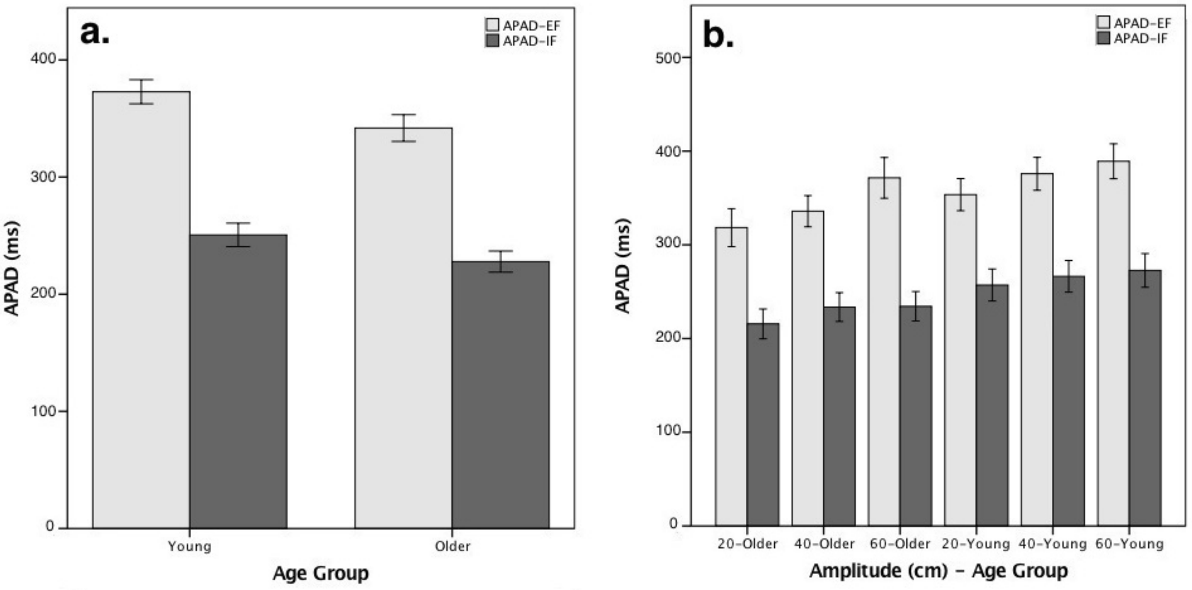

Figure 3-7. Mean anticipatory postural adjustment duration (APAD) as a function of age group and amplitude - age group. Figure 3-7.a. shows the difference in APAD between young and older adults for the soleus muscle in stance condition. Figure 3-7.b. shows APAD plotted against the different movement amplitudes separated by age for soleus muscle in stance condition. Error bars reflect standard error of the mean.

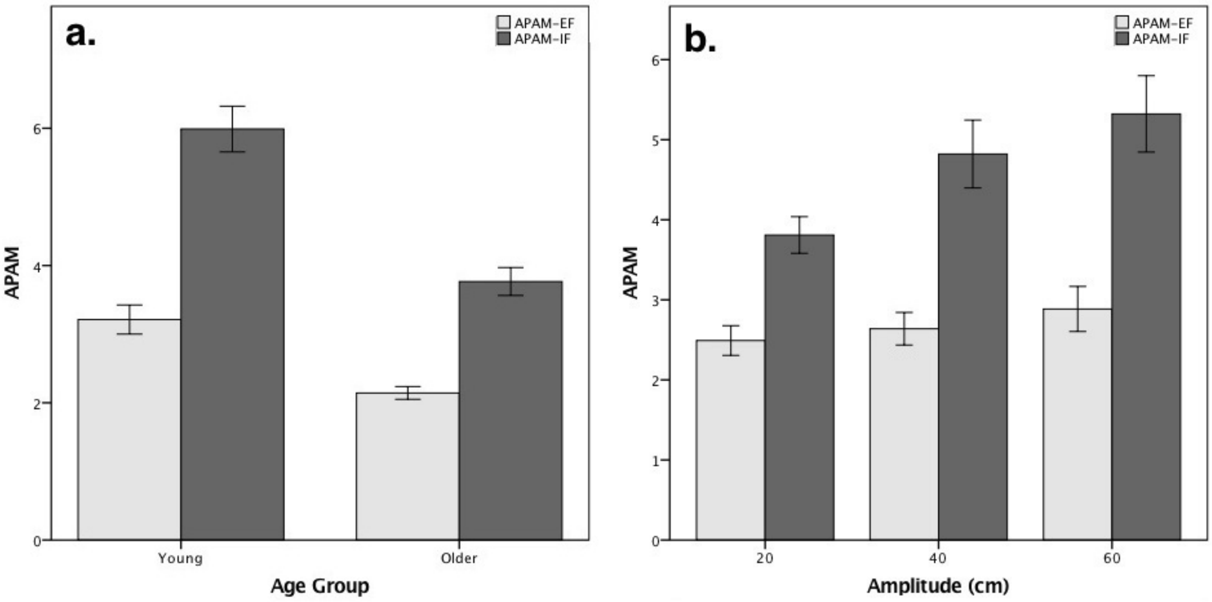

Figure 3-8. Mean anticipatory postural adjustment magnitude (APAM) as a function of age group and amplitude. Figure 3-8.a. shows the difference in APAM between young and older adults for the soleus muscle in stance condition. Figure 3-8.b. shows APAM plotted against the different movement amplitudes for moving tibialis anterior muscle. Error bars reflect standard error of the mean.

CHAPTER 4: ANTICIPATORY POSTURAL ADJUSTMENTS AMONG PEOPLE POST-STROKE DURING A FITTS' TASK: THE EFFECT OF DIFFERENT ATTENTIONAL FOCI

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Contributions of Authors to The Manuscript

In this manuscript, I designed the study, conducted an extensive literature search and carried out initial pilot trials to test the experimental protocol. Feedback from Drs. Passmore, Glazebrook, Sibley and Singer regarding the study's protocol was adopted in order to enhance the study's rigor. I wrote the ethics application, recruited and screened participants and collected all the data. Dr. Pooyania facilitated patient recruitment and provided further feedback on the study procedure. Working in collaboration with Drs. Passmore, Glazebrook and Singer I developed a procedure for analyzing the data. I wrote the manuscript for the study and subsequently shared it with the co-authors. All authors critically revised the manuscript for intellectual content and approved the final draft for submission. I have prepared the manuscript and it was submitted for publication to *Human Movement Science* Journal February 2019, and is currently under review.

Preface

In this manuscript we continue to build on findings obtained from the previous two studies in this thesis. Patients after stroke suffer from a great likelihood of falling. The increased likelihood of falling indicates that there is a great need for researching risk factors related to fall and establishing methods for assessing and modifying those risks. Falls occur as a result of compounding factors that combine and overwhelm an individual's ability to maintain or regain his or her balance. However, there is ample evidence to suggest that APA impairment leads to greater likelihood of falls. Several sources of evidence suggest that adopting an external focus of attention yields superior motor performance. Yet, there are no studies investigating the effects of different foci of attention on APAs among people after stroke. Given the importance of APAs and the potential information related to APAs and risk of falls that can be obtained from investigating this topic, we have decided to conduct this study.

The aim of this study is to investigate the effects of different attentional foci on APAs when performing a lower extremity Fitts' task among patients post-stroke. In this study we provide further corroboration to the beneficial effects of adopting an external focus of attention. Further, we discuss the lag in the uptake of this concept in rehabilitation settings. We also provide some insights into the task used in our study and how the impairment level of the participants affected their performance. The results of this study provide important information for clinicians who are involved in balance rehabilitation and for researchers in the fields of motor control and learning and rehabilitation.

The following manuscript is presented as it was submitted to the *Human Movement Science* Journal February 2019.

Abstract

People after stroke often have postural impairments that can increase their risk of falling. Anticipatory postural adjustments (APAs) are changes in the activity of postural muscles prior to a voluntary movement in order to maintain vertical equilibrium. Previous research suggests that improving APAs leads to better postural control and reduces the risk of falls. Consistent evidence supports that an external focus of attention (i.e., focusing on the effects of movement), as opposed to an internal focus of attention (i.e., focusing on the movement itself), yields better performance of motor skills that include postural control. Our study aimed to investigate the effects of different attentional foci on APAs when performing a lower extremity Fitts' task. Twelve individuals who had a stroke performed a lower extremity Fitts' task while adopting an external focus or an internal focus of attention. A motion capture system was used to determine behavioral and kinematic measures, and electromyography was used to measure APAs duration and magnitude. The results showed that an external focus of attention yields significantly better performance on all outcome measures. The improvement in performance is seen in shorter movement times, higher peak velocities, earlier APAs onset and more efficient APAs magnitude. These changes in outcome measures suggest that adopting an external focus of attention during postural control tasks could be effective in improving balance control and reducing the risk of falls among people after stroke. Future research is recommended to investigate the implementation of this technique (adopting an external focus) into standard clinical practice.

4.1. Introduction

Stroke is one of the major contributors to morbidity and mortality worldwide (Norrving & Kissela, 2013; World Health Organization, 2008). It is estimated that over 70% of the people who survived a stroke suffer from post-stroke impairments that affect their quality of life and activities of daily living (ADL) (Norrving & Kissela, 2013; World Health Organization, 2008). There is a great need for post-stroke rehabilitation, which means developing better assessment tools and more effective therapeutic interventions. People post-stroke present with a variety of sensorimotor impairments; however, one particular sequela of stroke – impaired postural control – is likely to cause the greatest impact on ADL independence and gait (Bohannon & Leary, 1995; Geurts, de Haart, van Nes, & Duysens, 2005; Keenan, Perry, & Jordan, 1984). Postural control –defined as the ability to control the body's position in space for the combined purposes of stability and orientation (Shumway-Cook & Woollacott, 2012)– is essential for ADL activities and gait and its impairment among people post-stroke is linked to a high incidence of falls both during the rehabilitation phase and thereafter (Alemdaroglu, Ucan, Topcuoglu, & Sivas, 2012; Weerdesteyn, de Niet, van Duijnhoven, & Geurts, 2008).

Anticipatory postural adjustments (APAs) are changes in the activity of postural muscles prior to a voluntary movement in order to maintain vertical equilibrium (Massion, 1992). These APAs are an essential component of postural control and are the first line of defense against falling (Aruin, 2016; de Azevedo, Claudino, Conceicao, Swarowsky, & Santos, 2016; Kanekar & Aruin, 2014). Several studies investigating APAs suggest that an impairment of postural adjustments is linked to a higher likelihood of falls (Horak, 2006; Hyodo et al., 2012; Uemura, Yamada, Nagai, & Ichihashi, 2011). When reviewing the available literature for APAs among people post-stroke, evidence suggests that people after stroke show a tendency of decreased, delayed and dysfunctional APAs in both lower extremities during stepping tasks (Hedman, Rogers, Pai, & Hanke, 1997; Horak, Esselman, Anderson, & Lynch, 1984; Slijper, Latash, Rao, & Aruin, 2002; Sousa, Silva, & Santos, 2015). Clinical research indicates that improving APAs leads to better postural control and reduces the risk of falls (Aruin, Kanekar, Lee, & Ganesan, 2015; Kanekar & Aruin, 2015; Kubicki, Mourey, & Bonnetblanc, 2015; Saito, Yamanaka, Kasahara, & Fukushima, 2014).

Previous studies show that an earlier onset of APAs indicates greater postural preparation in anticipation of the expected disturbance associated with voluntary movement (e.g., step initiation) (Aruin et al., 2015). Further, improvement in APAs measures (e.g., earlier onset) is associated with improvement in motor performance during reaching tasks. The improvement in motor performance is seen as increased accuracy of movement, shorter movement time and higher peak velocity (Saito, Kominami, Yamanaka, Takeda, & Fukushima, 2011; Saito et al., 2014). Therefore, improvement in motor performance is often associated with overall better postural control. Additionally, it is unknown whether clinical indicators of physical impairment post-stroke are correlated with APAs and motor performance measures. If there is a significant correlation between the previous measures and physical impairment this may aid in identifying individuals who have a higher risk of falling. Although a number of studies investigated APAs among people post-stroke, only a limited number of studies investigated methods for improving APAs (Aruin, 2016; Aruin et al., 2015; Silva et al., 2018). Given the beneficial effects of improving APAs and their role in fall prevention it is important to develop methods for assessing and improving APAs.

The focus of attention concept has shown promise in eliciting beneficial effects during the performance of motor tasks. In this concept, Wulf and colleagues proposed that when performing a motor task, it is better to direct attention towards the effect of the movements on the environment (an external focus of attention) than directing attention on the movement itself (an internal focus of attention) (Wulf, Höß, & Prinz, 1998). Ample evidence supports that adopting an external focus is more beneficial for motor performance, including tasks that involve postural control (Wulf, 2013; Wulf & Lewthwaite, 2016). Further, adopting an external focus had been shown to improve movement effectiveness, movement efficiency and facilitate learning among a variety of populations, including people post-stroke (Fasoli, Trombly, Tickle-Degnen, & Verfaellie, 2002).

A novel approach to investigating APAs among post-stroke individuals could involve using Fitts' law to characterize the relationship between APAs parameters (e.g., electromyography [EMG] magnitude and duration) with the length of the step and size of the stepping target (Fitts, 1954). Previous research indicates that Fitts' law is a useful tool for systematically altering the difficulty of goal-directed movements (McCrea & Eng, 2005; Winstein & Pohl, 1995; Zimmerli et al., 2012). When examining the relevant literature investigating the relationship between APAs and Fitts' law's parameters, studies suggest that APAs are predictable when participants performed a Fitts' task (Bertucco & Cesari, 2010; Bertucco, Cesari, & Latash, 2013; Danion, Duarte, & Grosjean, 1999; Duarte & Freitas, 2005; Duarte & Latash, 2007; Juras, Slomka, & Latash, 2009). However, in the previous studies most participants were healthy young adults and no study included people after stroke. Further, no previous study examined the potential benefits of adopting an external focus of attention on APAs among patients post-stroke.

4.1.1. Aims and Hypotheses

The primary aim of this study was to investigate the effects of different foci of attention on APAs parameters (measured as EMG magnitude and duration) when performing a lower extremity Fitts' task among people post-stroke. The secondary aims were: (1) to compare the differences in performance measured using movement time (MT), peak velocity (PV), time to peak velocity (ttPV) and variability at target endpoint (SDT) when adopting different attentional foci; and (2) to examine the correlation between physical impairment (assessed using the Chedoke-McMaster Stroke Assessment [CMSA] leg and foot subscales), APAs parameters and motor performance measures (MT, PV, ttPV and SDT).

Based on our literature review, we hypothesized that when adopting an external focus participants would show earlier APAs onset and more efficient (lower) APAs magnitude. In addition, when adopting an external focus of attention participants would show shorter MT, higher PV, shorter ttPV and smaller SDT. In regard to the correlation between the physical impairment measure and the outcome measures, we anticipate a significant correlation between CMSA subscales, APAs parameters and motor performance measures.

4.2. Methods

4.2.1. Participants

Twelve participants were recruited for this study. Recruitment of participants was carried out both in the community and within local health care and rehabilitation centers. An a priori power calculation ($\beta = 0.8$, $\alpha = 0.05$) with published data for APAs onset time during lower extremity stepping tasks determined a sample size of 9 participants was sufficient. All participants in our study provided an informed consent prior to data collection. The Health Research Ethics Board at the University of Manitoba approved all procedures.

4.2.2. Inclusion and Exclusion Criteria

The inclusion criteria for the study included the following: (i) clinical diagnosis of no more than one stroke (either ischemic or hemorrhagic) experienced more than 1 month prior to study enrollment; (ii) age ≥ 18 years; and, (iii) ability to stand independently without aid. The exclusion criteria included the following: (i) spasticity in the hemiparetic lower extremity defined as a score of more than or equal to 3 on the modified Ashworth scale (Bohannon & Smith 1987); (ii) diagnosis of terminal illness, life-threatening co-morbidity or concomitant neurological or psychiatric illness; (iii) severe aphasia or cognitive impairment affecting their ability to provide informed consent for the study; and, (iv) score less than 45 on the Berg balance scale.

The cut-off score on the Berg balance scale was deemed necessary because the task in this study required participants to stand independently and perform a lower extremity task with one foot, while supporting weight on the other lower extremity. This score -45- was determined as previous research indicates that people post-stroke with this score and higher were more likely to show greater balance ability (Andersson, Kamwendo, Seiger, & Appelros, 2006; Berg, Wood-Dauphinee, & Williams, 1995; Dogan, Mengulluoglu, & Ozgirgin, 2011). Leg and foot physical impairment was assessed using the CMSA leg and foot subscales (Gowland et al., 1993). The CMSA leg and foot sub-scales of the impairment inventory were used to determine participants' motor recovery. Each sub-scale is rated between stages 1 to 7, where lower scores indicate more impairment and 7 indicates full or almost full recovery of function. One consistent author (SA), who is experienced with the above tests, always administered the previous measures. The affected side (i.e., hemiparetic side) was noted prior to commencing the study. Participants were asked to use the hemiparetic lower extremity to perform the motor task in this study.

4.2.3. Apparatus

The instruments that were used in this study included an optoelectronic motion capture system and an EMG system. The motion capture system used for this study was the Optotrak 3D-investigator (Northern Digital Inc. [NDI], Waterloo, Canada). This system records the 3-dimensional displacement of infrared-emitting diode markers. The displacement of two markers was recorded using this system. These two markers were placed bilaterally on the distal aspect of the great toe. Data were collected at 200 Hz.

The EMG system used for this study was the Power 1401 data acquisition system, the 1902 amplifier with a 4-channel electrode adaptor box and the software 'Signal' (Cambridge Electronic Design [CED], UK). This EMG system uses snap connection leads to attach to disposable pre-gelled Ag/AgCl, bipolar electrodes that mount directly to the skin with an adhesive pad. The EMG signal was sampled at 2000 Hz. Muscle activity of the soleus and tibialis anterior muscles were recorded. These muscles were chosen because they are part of the main lower extremity postural muscles and can provide an overall representation of APAs (Nashner 1977). The above muscles in the stance and moving limbs were recorded. Electrode placement for EMG was done in accordance with Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al., 2000; Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). The Optotrak and EMG systems were synchronized during data collection using a trigger pulse and linked to their respective software and computer.

4.2.4. Procedure

The protocol for this study involved participants standing with bare feet on a level surface with their feet shoulder-width apart and their arms at their sides. Participants were asked to align the distal tips of both great toes to a straight line shown on the floor in front of them (i.e., the starting position). An adjustable walker was placed in front of participants, and to this walker, a digital projector was mounted to project 30-inch images on the floor. Each participant was instructed to step (with the hemiparetic side) and place the tip of the great toe on a square target on the floor displayed by the projector. Targets had a predefined width (W) and were located at a predefined amplitude (A). Target position was anterior to the participant, in the sagittal plane. The task in this study involved a single discrete movement to the target. The instructions given to each subject prior to a block of trials was a typical Fitts' task instruction: "be as fast and as accurate as possible in your pointing movement." Participants were asked to hold the position of the foot after completing the task until the end of trial in order to ensure proper data collection.

Each trial lasted 10 seconds and it started with the participant standing in the starting position. The image for the block of trials was presented to the participant. A 'go' auditory signal from the computer system indicated that participants should initiate the movement towards the target. Three movement amplitudes (A=20, 40 and 60 cm) and three target widths (W=2.5, 5 and 10 cm) were used in this study. The combinations of these amplitudes and widths yield 9 different conditions (Figure 4-1). The amplitude was measured from the center of the target to the line of the starting position. The nine combinations were presented in a random order, with each combination presented six times. Participants were given practice trials (1-3) prior to each condition. Once completed, the procedure was repeated with the same foot (108 trials total) in order to investigate the effects of different attentional foci.

Investigating focus of attention involved providing participants with additional instructions during trials for controlling focus of attention. During the internal focus of attention condition participants were told to "focus on your foot; concentrate on your foot's motion when you reach forward with your foot." During the external focus condition, participants were told to "focus on the target; concentrate on the middle of the target." Half of the participants performed the experiment under the internal focus followed by the external focus condition, while the other half of participants started with the external focus followed by the internal focus condition. Instruction reminders (for Fitts' task and focus of attention) were provided to participants prior to each Fitts' task condition.

4.2.5. Data processing and analyses

4.2.5.1. Data processing. Data processing was done using a custom computer software developed using Matlab (release 2014b, The Mathworks Inc., USA). For kinematic data, only sagittal plane data were analyzed, as this was the main plane of movement. Position data were low-pass filtered at 10 Hz. Peak velocity (PV), measured in millimeter/second (mm/s), and time to peak velocity (ttPV), measured in millisecond (ms), were determined from the velocity profile in the sagittal plane of the marker on the great toe of the moving foot. We defined PV as the greatest velocity attained in the sagittal plane of movement by the great toe. The ttPV definition was the time following movement onset to reach peak velocity (ms). Movement onset (T_0) was defined as the first frame when velocity in the primary axis of movement reached 35 mm/s during a particular trial. Movement end time (T_{END}) was defined as the first frame after T_0 when velocity in the primary axis of movement fell below 35 mm/s and remained below for at least 100ms. Movement time (MT) was defined as the time between T_0 and T_{END}. Variability at target (SD_T) was estimated in the primary axis of movement using the standard deviation of the movement endpoints relative to the center of the target.

For EMG data, the raw signals were first band-pass filtered (40-500 Hz), then full-wave rectified and then low-pass filtered at 10 Hz. A zero-lag, 4th order Butterworth filter was used for processing. Subsequently, onset of EMG activity (T_{0_EMG}) was determined by detecting the first increase above 2 *SDs* from EMG baseline. Baseline level was defined as the mean EMG activity between 100 and 400 ms of data recording. The net time between T_{0_EMG} and T_0 was defined as APA duration (APA_D). To quantify APA magnitude (APA_M) the following procedure was done. First, the integral of EMG activity from 100 ms to 400 ms (i.e., EMG background) was determined ($Integ_{100\text{-}400}$). Second, the integral of EMG activity from T_{0_EMG} to T_0 was determined ($Integ_{T0EMG\text{-}T0}$). Finally, the APA_M measure was defined as the following ratio: $APA_M = (Integ_{T0EMG\text{-}T0} - Integ_{EMG100\text{-}400}) / Integ_{EMG100\text{-}400}$ (Figure 4-2).

The EMG data for both limbs (stance and moving) were processed to obtain APA_D and APA_M.

4.2.5.2. Dependent variables and statistical analyses. The dependent variables were: MT, PV, ttPV, SD_T, APA duration (APA_D) and APA magnitude (APA_M). For all dependent variables separate: 2 foci of attention x 3 amplitudes x 3 target widths, mixed model analyses of variance (ANOVA) with repeated measures were conducted. Measures of APAs (duration and magnitude) were collapsed for both right and left legs and were separated as stance and moving. Foci of attention, amplitude and width were all within-subjects factors. We tested for simple effects on interactions and we have adjusted alpha (α) for post-hoc tests. Post-hoc analyses were performed using Tukey's HSD procedure. A preliminary analysis was performed to confirm that order didn’t interact with attentional focus. The analysis involved comparing participants who started with an internal focus against those who started with an external focus. Additionally, Spearman’s Rho (ρ) correlation analysis was used to investigate the relationship between the dependent variables and CMSA-leg and –foot subscales. Statistical analyses were performed using SPSS statistical package software. Only significant values are reported in the results below.

4.3. Results

Twelve people post-stroke (four females and eight males) participated in our study. None of the participants were undergoing active rehabilitation at the time of the study. The session time required to complete the experiment was 1.5-2.5 hours (mean=1.93). Mean age was 62.5 years (±14.41) and mean time since stroke was 15.7 months (±11.5). Summary of participants' characteristics is shown in Table 4-1.

4.3.1. Behavioral and Kinematic Measures

4.3.1.1. Movement Time. MT was significantly lower with an external focus of attention compared to an internal focus, $F(1,11) = 50.8$, $p<0.001$, $\eta_p^2=0.82$ (Figure 4-3.a). In addition, higher amplitude resulted in longer MT, $F(2, 22) = 95.9$, $p<0.001$, $\eta_p^2=0.89$ (Figure 4-3.b). No significant interactions were found. Post hoc analyses showed that all amplitudes resulted in different MTs, $p<0.001$. No significant effects were found for width. All other comparisons were not significant.

4.3.1.2. Peak Velocity. PV was significantly higher with an external focus of attention compared to an internal focus, $F(1,11) = 27.7$, $p<0.001$, $\eta_p^2=0.72$. Results also showed that as amplitude increased PV increased, $F(2, 22) = 203.3$, $p<0.001$, $\eta_p^2=0.95$ (Figure 4-4.a). Also, as width increased PV increased, $F(2, 22) = 18.9$ $p<0.001$, $\eta_p^2=0.63$ (Figure 4-4.b). Significant interactions were found for amplitude by width, $F(4, 44) = 3.4$ $p<0.05$, $\eta_p^2=0.23$. Post hoc analysis showed that all amplitudes resulted in different PV, $p<0.001$ and width only led to different PV when amplitude was 20cm, $p<0.01$. All other comparisons were not significant.

4.3.1.3. Time to Peak Velocity. Results showed that ttPV was significantly shorter with an external focus compared to an internal focus, $F(1,11) = 11.7$, $p<0.01$, $\eta_p^2=0.52$. In addition, higher amplitude resulted in longer ttPV, $F(2, 22) = 16.1$ $p<0.001$, $\eta_p^2=0.59$. Smaller width resulted in longer ttPV, $F(2, 22) = 6.2$ $p<0.001$, $\eta_p^2=0.36$. No significant interactions were found. Post hoc analysis indicated that all amplitudes and widths resulted in different ttPV, $p<0.05$. All other comparisons were not significant.

4.3.1.4. Variability at Target. SD_T was significantly smaller with an external focus of attention compared to an internal focus, $F(1,11) = 18.1$, $p<0.01$, $\eta_p^2=0.62$. Results also showed that shorter amplitude led to smaller SD_T, $F(2, 22) = 14.7$, $p<0.001$, $\eta_p^2=0.57$ (Figure 4-5.a). Significant interactions were found for focus of attention by amplitude $F(2, 22) = 3.9$, $p<0.05$, $\eta_p^2=0.26$. Post hoc analyses showed that 20 and 60cm amplitudes resulted in significantly different SD_T ($p<0.01$). No significant effects were found for width (Figure 4-5.b). All other comparisons were not significant.

4.3.2. Anticipatory Postural Adjustments Measures

4.3.2.1. Anticipatory Postural Adjustments Duration. Results showed that adopting an external focus of attention led to earlier onset of APAs for both muscles, tibialis anterior (TA) and soleus (SO) of both legs, moving and stance, TA moving: $F(1,11) = 35.6$, $p<0.001$, $\eta_p^2=0.76$, TA stance: $F(1,11) = 26.1$, $p<0.001$, $\eta_p^2=0.71$ (Figure 4-6.a), SO moving: $F(1,11) = 70.5$, $p<0.001$, $\eta_p^2=0.86$, and SO stance: $F(1,11) = 39.4$, $p<0.001$, $\eta_p^2=0.78$. No significant effects were found for amplitude or width (Figure 4-6.b). All other comparisons were not significant.

4.3.2.2. Anticipatory Postural Adjustments Magnitude. APA_M was significantly smaller with an external focus of attention compared to an internal focus for both TA and SO of both legs moving and stance, TA moving: $F(1,11) = 12.5$, $p<0.05$, $\eta_p^2=0.53$ (Figure 4-7.a), TA stance: $F(1,11) = 17.8$, $p<0.01$, $\eta_p^2=0.62$, SO moving: $F(1,11) = 25.4$, $p<0.001$, $\eta_p^2=0.69$, and SO stance: $F(1,11) = 22.8$, $p<0.001$, $\eta_p^2=0.67$. No significant effects were found for amplitude or width (Figure 4-7.b). All other comparisons were not significant.

4.3.3. Correlation Analysis

Results of correlation analyses are shown in Table 4-2. Overall, there was a significant negative correlation between variability at target and CMSA-leg and –foot scores. As CMSA scores increased, variability at target decreased. There was also a significant correlation between APAs measures and CMSA-leg and –foot scores. As the CMSA scores of participants were higher, the higher were measures of APAs (i.e., earlier APAs activation and higher magnitude).

4.4. Discussion

It is important to investigate methods for assessing and improving APAs, as they are the first line of defense against falling. Further, previous research on focus of attention suggests that adopting an external focus of attention improves motor performance and may also improve APAs during a lower extremity Fitts' task. In our study, we investigated the effects of different attentional foci on APAs and other movement parameters when performing a lower extremity Fitts' task among people post-stroke. We conducted this study in order to examine if the previously reported positive effects of adopting and external focus of attention during motor skills are found in APAs among people post-stroke.

Participants benefited from adopting an external focus of attention. Improved performance can be seen in the shorter movement times, larger peak of velocities, shorter times to peak velocity and improved accuracy of reaching the target. Moreover, the benefits of adopting an external focus were evident in measures of APAs, as APAs occurred earlier with an external focus and APAs magnitude was smaller and more efficient. These findings are similar to previous studies that indicate that improvements in motor performance (e.g., shorter movement times and larger peak velocities) are associated with improvement in APAs measures (Saito et al., 2011; Saito et al., 2014). Further, the improved performance found in our study when adopting an external focus of attention is similar to previous research indicating that external focus of attention is more beneficial than an internal focus (Wulf, 2013; Wulf & Lewthwaite, 2016).

The positive effects of adopting an external focus of attention can be explained by the constrained action hypothesis proposed by Wulf and colleagues (Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001). According to this hypothesis adopting an internal focus promotes conscious control of movement, thus interfering with automatic control processes. Conversely, adopting an external focus facilitates automaticity by using unconscious, fast, and reflex-like control processes. Several studies examined this hypothesis and provide evidence related to: changes in attentional capacity (Kal, van der Kamp, & Houdijk, 2013; Wulf, McNevin, et al., 2001); movement-adjustments frequency (McNevin, Shea, & Wulf, 2003; Wulf, Shea, et al., 2001); reduced reaction time detected under different attentional foci (Lohse, 2012); and, neural control with different attentional foci (Huang, Zhao, & Hwang, 2014).

In this study we have utilized both attentional focus instructions and a Fitts’ law task to examine people post-stroke APAs and motor performance. We utilized a Fitts’ law task in our study as previous research reported that APAs are predictable among non-disabled young adults when performing a Fitts’ task (Bertucco & Cesari, 2010; Bertucco et al., 2013; Danion et al., 1999; Duarte & Freitas, 2005; Duarte & Latash, 2007). However, APAs performance within the context of Fitts’ law tasks is unknown among people post-stroke. Further, utilizing a Fitts’ task is beneficial in terms of eliminating confounding aspects of the motor task such as a learning effect; as Fitts’ law is resistant to learning (Schmidt & Lee, 2011). The use of Fitts’ law to examine APAs provides specific parameters of the motor task and thus can help identify the presence and extent of APAs impairment. Therefore, the task in our study can be used as a performance-based objective outcome measure of APAs.

In our study, the results show that, regarding Fitts' law parameters, amplitude of movement had more effect on our behavioral and kinematic measures than width of target. Amplitude of movement had a significant effect on all four behavioral and kinematic outcome measures; however, width only affected peak velocity and time to peak velocity. Further, the effect size of width in the previous outcome measures was smaller than the effect size of amplitude. Our finding that there were no significant effects for width on variability at target suggests an important implication. It was possible that participants in our study adjusted their movement planning mainly based on the amplitude of movement. Further, this finding suggests that the perception of people post-stroke of a target width is more affected than their perception of a distance to a target. Therefore, during training of individuals post-stroke to perform a task similar to the one used in our study (e.g., gait initiation), it is more important to emphasize the amplitude of movement than the target size of the end of a step. Nonetheless, considering amplitude as the main predictor of movement time violates Fitts' law and contradicts its seemingly universal applicability. However, previous research investigating lower extremity movement while performing a Fitts' task had also reported similar findings (Bertucco & Cesari, 2010; Duarte & Latash, 2007; Passmore et al., 2015).

The violation of Fitts' law found in our study may be explained by the nature of a lower extremity reaching movement while standing. Unlike the upper limb, the lower limb inherently involves an upward circular motion when reaching forward. Thus, when reaching for a target 40 cm away with the lower extremity (while standing), the overall distance covered would likely be more than 40 cm. As the lower extremity moves forward, this motion involves flexing the knee upward and then attempting to reach the target. However, with the upper extremity, when performing a reaching task, the distance covered is likely near the amplitude designated to the Fitts' task. The effect of amplitude on lower extremity reaching can be demonstrated when examining our results of peak velocity. The results showed that at the lower amplitude of movement (20 cm), the different amplitudes and widths used in our study led to different peak velocities (Figure 4-4-b). However, when examining all the different combinations of amplitude and width, the differences in peak velocities diminished except for amplitude. The previous result could also suggests that participants were treating all target widths as the same size with increased amplitude as perhaps the task was becoming difficult. Therefore, not all factors related to the motor task were accounted for in our study's task – for example, the height of movement.

For APAs measures both parameters of Fitts' law (amplitude and width) did not significantly affect APAs duration or magnitude. It is possible that participants in our study compensated for the different amplitudes and widths with a more rapid step (i.e., increased velocity). In fact, our results suggest that participants did increase their velocity with increased amplitude. Therefore, with increasing the velocity of stepping movements with increased amplitude, the differences in APAs parameters (duration and magnitude) between the different amplitudes were diminished. Furthermore, as mentioned above, Fitts' law does not take into account the overall height of a step. Previous studies that investigated similar motor tasks (e.g., step initiation) found that overall height of a step had a significant effect on APAs (Yiou, Artico, Teyssedre, Labaune, & Fourcade, 2016). In a study by Yiou et al., (2016), the authors asked participants to take a step over an obstacle. The distance to the obstacle was variable as well as the height of these obstacles. Results showed that the anticipatory peak of center of the pressure (COP) mediolateral (ML) shift, the initial center of the mass (COM) ML velocity and the duration of swing phase of gait increased with obstacle height, but not with obstacle distance. For the anteroposterior (AP) component of APAs, anticipatory peak of backward COP shift and the initial forward COM set decreased with obstacle height. Further, the forward COM velocity at foot-off increased with obstacle distance. These findings suggest that step height does influence APAs during lower extremity stepping movement.

For the CMSA-leg and -foot subscales, the correlation analyses indicated that there were significant correlations between CMSA subscales and APAs measures. Also, there was a significant correlation between CMSA subscales and variability at target endpoint. These findings suggest that the participants' impairment level was closely related to how well he/she performed the task. Similar findings were also shown in a previous study that investigated APAs (Garland, Gray, & Knorr, 2009). In this study authors indicated that lower CMSA-leg and foot scores were associated with a paucity of APAs activation (Garland et al., 2009). In our study, as the scores on the CMSA subscales were higher the better was the performance of the participants. Therefore, when designing a rehabilitation program, it is crucial that the skill levels of patients are individually taken into consideration.

The most noticeable finding in our study was that adopting an external focus yields positive effects on behavioral, kinematic and APAs measures when performing a motor task. These findings were corroborated by previous research that had also reported similar findings among non-disabled young and healthy adults as well as patients with neurological impairments (Wulf, 2013; Wulf & Lewthwaite, 2016). Despite this evidence, there is paucity in adopting focus of attention instructions in community and rehabilitation settings. Several studies showed that during training of motor skills, clinical practitioners provide learners with statements that promote an internal focus of attention (Durham, Van Vliet, Badger, & Sackley, 2009; Johnson, Burridge, & Demain, 2013; Porter, Wu, & Partridge, 2010). Future efforts are needed to promote the uptake of utilizing this technique –adopting an external focus of attention– during the training of motor skills. A limitation to our present results is that we only included a specific portion of people post-stroke who had a high score -45- on the Berg balance scale. Therefore, the findings in our study cannot be extended to all people post-stroke.

4.5. Conclusion

In conclusion, the results of our study suggest that an external focus of attention may improve APAs among people post-stroke when performing a lower extremity Fitts' task. Further, improvements in behavioral and kinematic measures can be seen when adopting an external focus of attention. Therefore, further research is warranted to investigate the effects of adopting an external focus of attention for people post-stroke in clinical trials. By comparing the provision of conventional therapeutic programs with either an emphasis on an external focus of attention versus control focus of attention. In addition, it is important to assess if the benefits of adopting an external focus of attention are maintained following the therapeutic program.

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Table 4-1. Participants' Characteristics

Demographics	**Value**
N (males/females)	12 (8/4)
Age mean (SD)	62.5 years (14.4)
Height mean (SD)	176.2 cm (5.9)
Hemiparetic side	4 right and 8 left hemiparesis
Type of stroke (ischemic/hemorrhagic)	11/1
Time since stroke mean (SD)	15.7 months (11.5)
Berg balance scale* score median (range)	50.5 (45-54)
CMSA†-leg score median (range)	5 (4-7)
CMSA†-foot score median (range)	5 (3-6)

SD: Standard deviation; CMSA: Chedoke-McMaster Stroke Assessment.

*Berg balance scale is a 14-item observational rating scale that provides a measure of functional balance and has an overall score of 56.

†The CMSA leg and foot sub-scales of the impairment inventory are two subscales used to determine the motor recovery of the leg and foot. Each sub-scale is rated between stages 1 to 7, where lower scores indicate more impairment and 7 indicates full or almost full recovery of function.

Table 4-2. Results of Spearman's Rho (ρ) correlation analysis between dependent variables and the Chedoke-McMaster Stroke Assessment (CMSA) leg and foot subscales

Measures	MT	PV	ttPV	SD_T	APA_D	APA_M
CMSA-leg	-0.08	0.09	-0.03	-0.32*	0.28-0.64* †	0.29-0.56* †
CMSA-foot	-0.12	0.03	0.05	-0.29*	0.27-0.54* †	0.22-0.39* † ‡

MT: Movement time; PV: Peak velocity; ttPV: Time to peak velocity; SD_T: Variability at target endpoint; APA_D: Anticipatory postural adjustments duration; APA_M: Anticipatory postural adjustments magnitude

* Indicates statistically significant ($p < 0.05$)
† Indicates correlation for soleus muscles (stance and moving)
‡ Indicates correlation for tibialis anterior muscles (stance and moving)

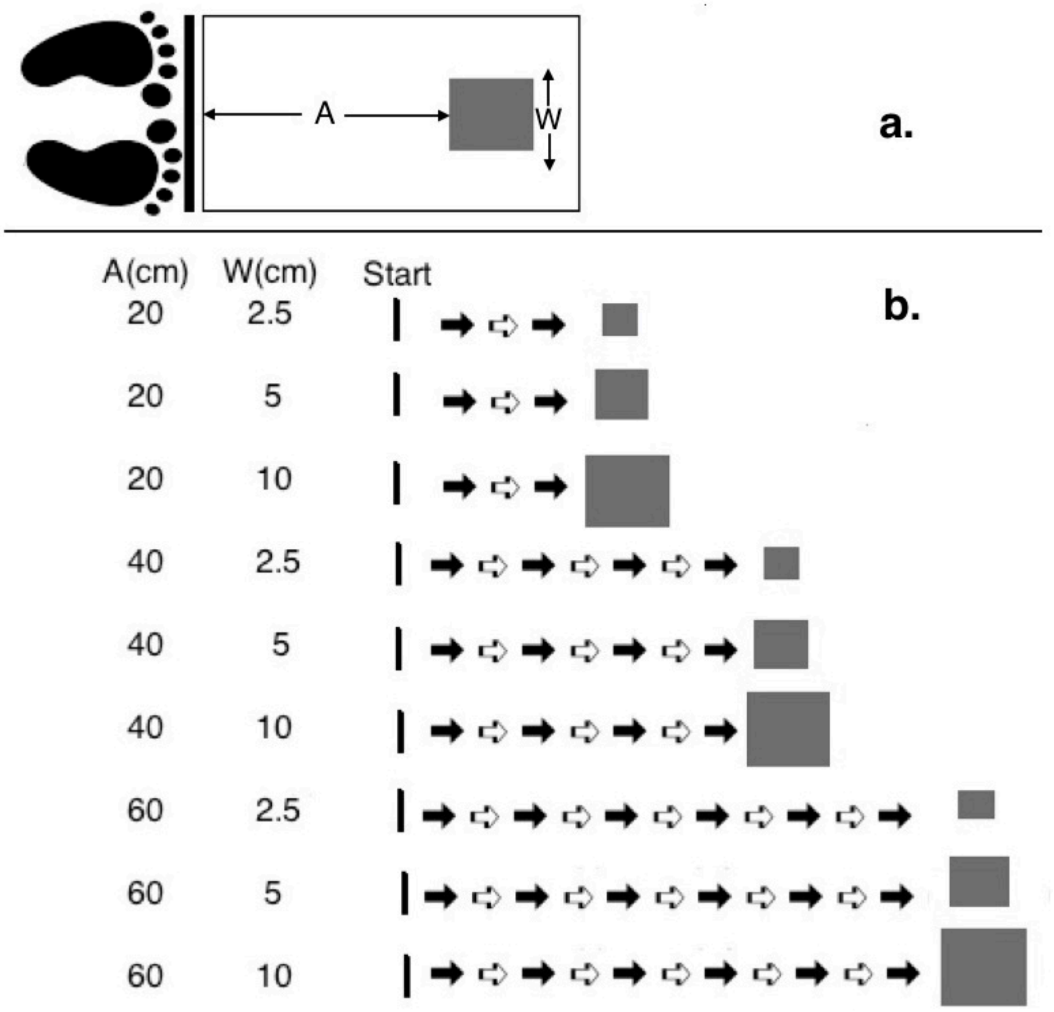

Figure 4-1. Experimental setup. Figure 4-1.a. shows the starting position for performing the task. Figure 4-1.b. shows the nine combinations of movement amplitude and target width. A=amplitude, W=width.

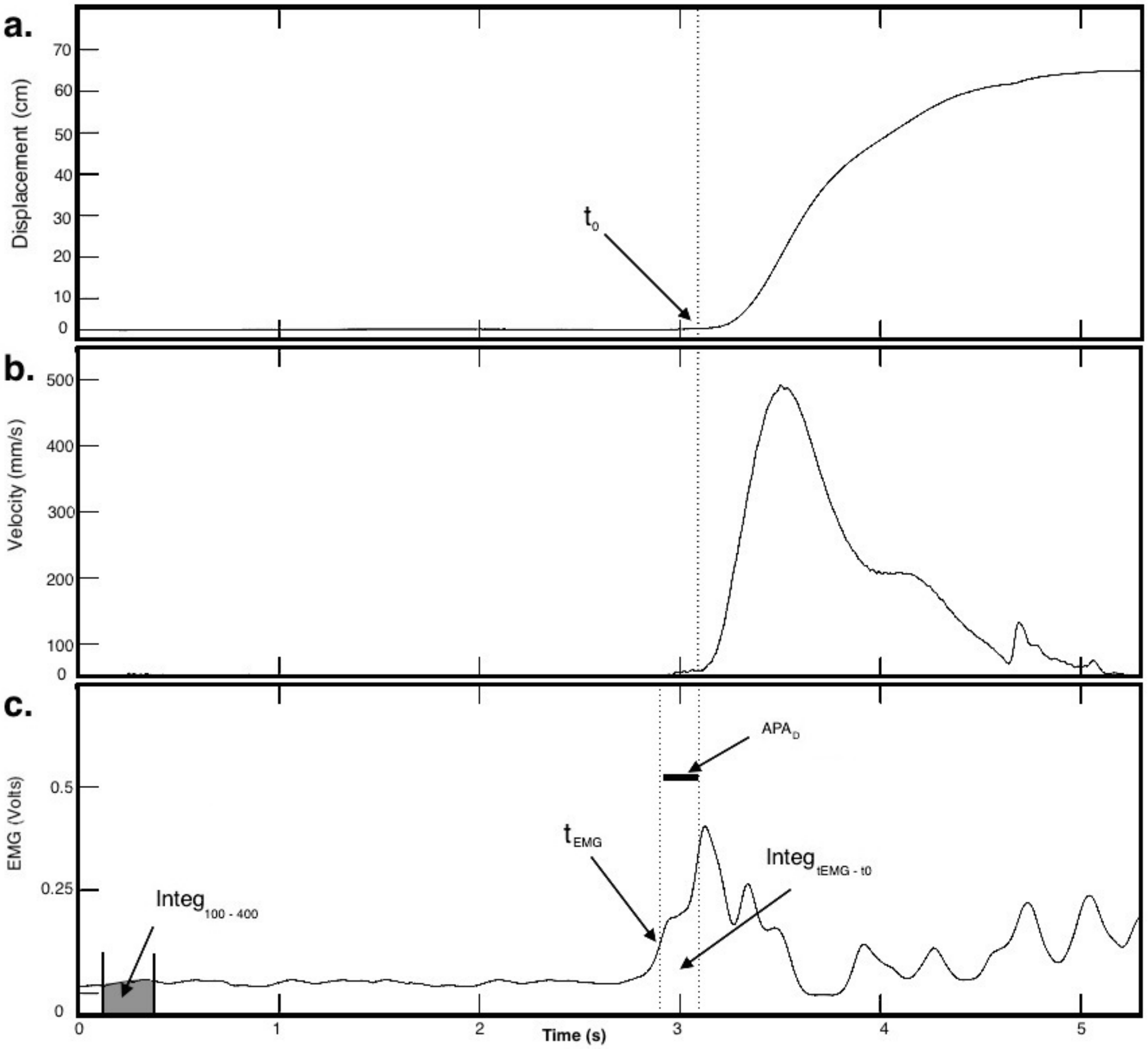

Figure 4-2. Example of a movement trial. Displacement and velocity profiles of the moving leg are shown in 4-2.a and 4-2.b. Movement onset is labeled as t_0. Figure 4-2.c shows the EMG profile for the soleus muscle of the stance leg. Beginning of EMG activity is labeled as t_{EMG} and the duration between t_{EMG} and t_0 is the duration of anticipatory postural adjustment (APA_D). The integral of EMG activity within APA_D was determined ($Integ_{tEMG-t0}$). Also, the integral of EMG between 100 to 400 ms was determined ($Integ_{100-400}$). Using $Integ_{tEMG-t0}$ and $Integ_{100-400}$, magnitude of anticipatory postural adjustment was determined.

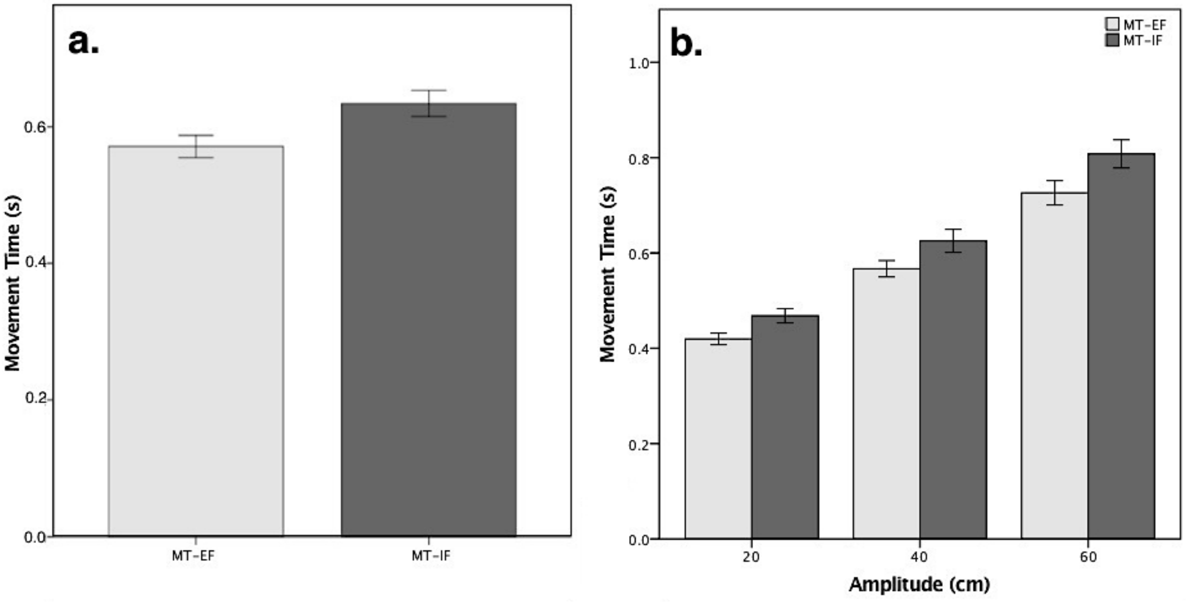

Figure 4-3. Mean movement time (MT) as a function of attentional foci and amplitude. Figure 4-3.a. shows the difference in MT when focusing externally (MT-EF) and when focusing internally (MT-IF). Figure 4-3.b. shows MT for internal and external focus plotted against the different movement amplitudes. Error bars reflect standard error of the mean.

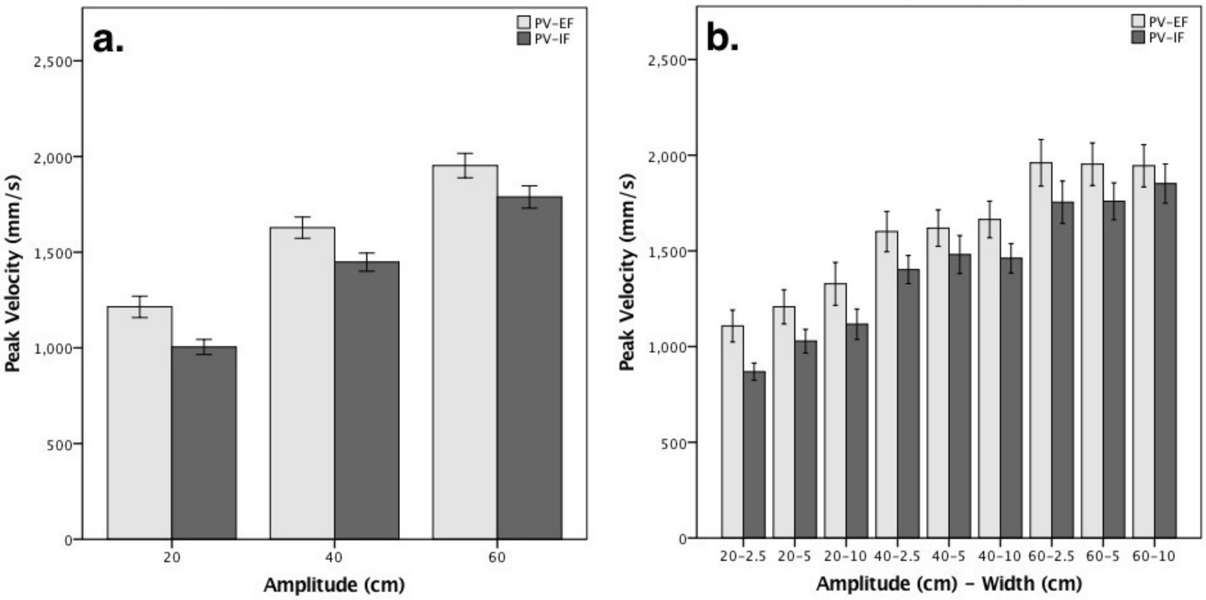

Figure 4-4. Mean peak velocity (PV) as a function of amplitude and amplitude - width. Figure 4-4.a. shows PV for internal and external focus plotted against the different movement amplitudes. Figure 4-4.b. shows PV plotted against the different combinations of movement amplitude and width. Error bars reflect standard error of the mean.

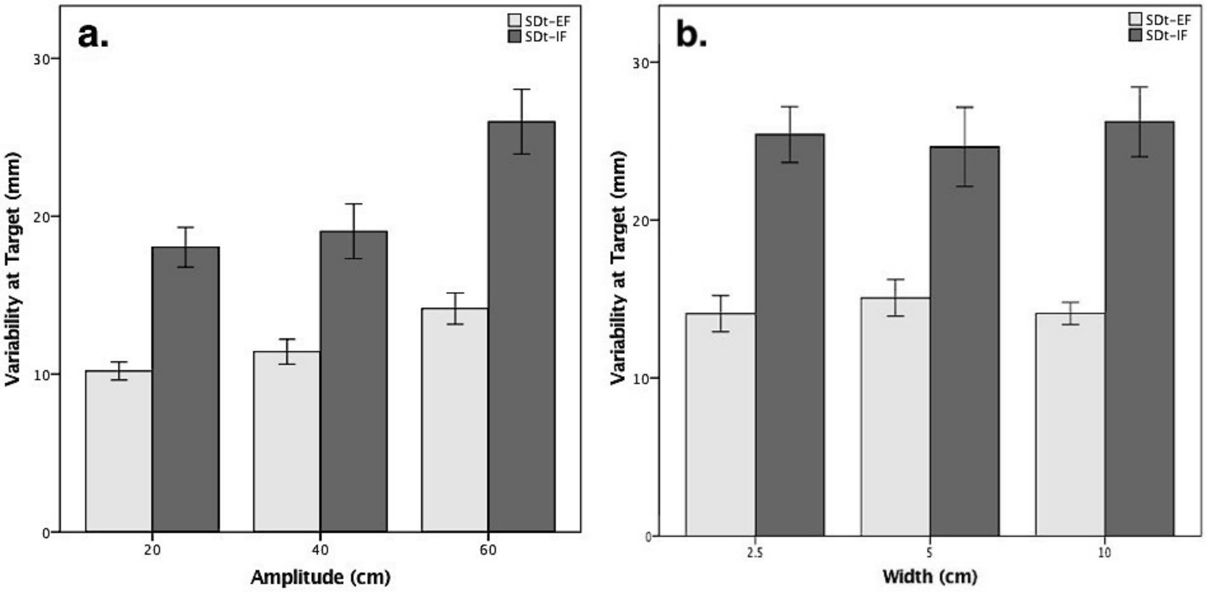

Figure 4-5. Mean variability at target (SDt) as a function of amplitude and width. Figure 4-5.a. shows SDt for internal and external focus plotted against the different movement amplitudes. Figure 4-5.b. shows SDt for internal and external focus plotted against the different target widths. Error bars reflect standard error of the mean.

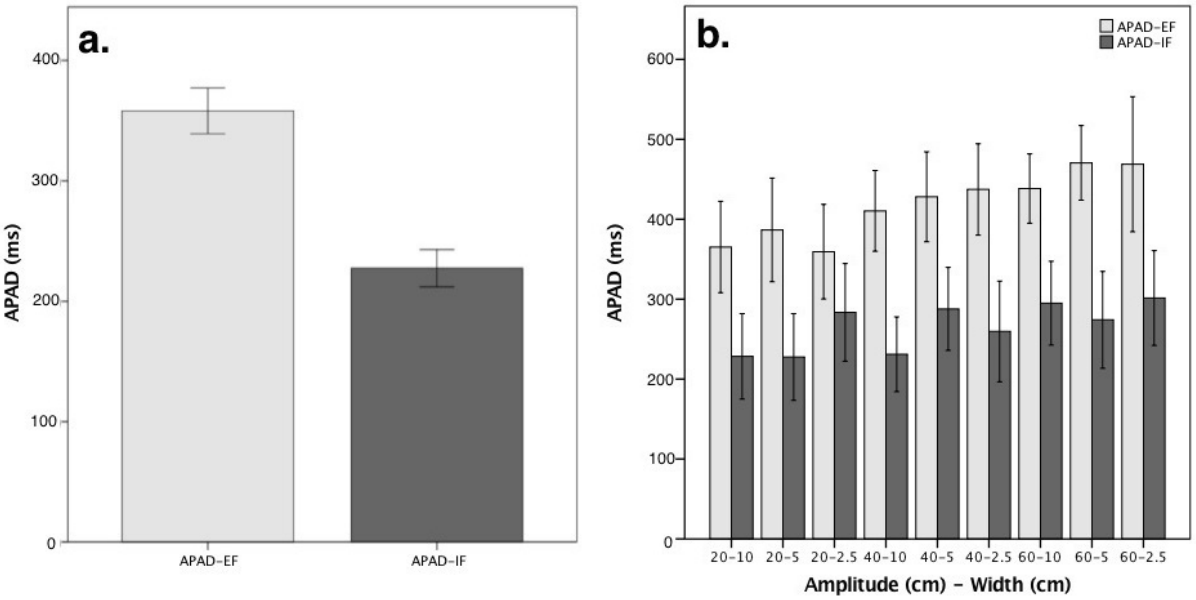

Figure 4-6. Mean anticipatory postural adjustment duration (APAD) as a function of attentional foci and amplitude - width. Figure 4-6.a. shows the difference in APAD when focusing externally (APAD-EF) and when focusing internally (APAD-IF) for the stance tibialis anterior muscle. Figure 4-6.b. shows APAD plotted against the different combinations of movement amplitude and width for moving soleus muscle. Error bars reflect standard error of the mean.

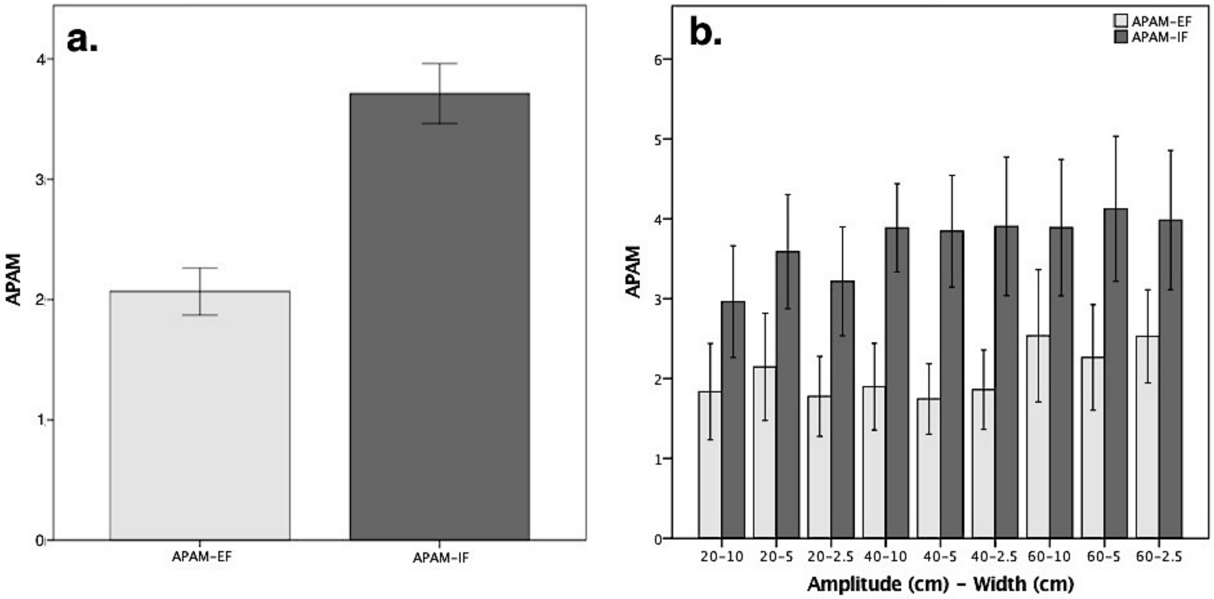

Figure 4-7. Mean anticipatory postural adjustment magnitude (APAM) as a function of attentional foci and amplitude - width. Figure 4-7.a. shows the difference in APAM when focusing externally (APAM-EF) and when focusing internally (APAM-IF) for the moving tibialis anterior muscle. Figure 4-7.b. shows APAM plotted against the different combinations of movement amplitude and width for the stance soleus muscle. Error bars reflect standard error of the mean.

CHAPTER 5: GENERAL CONCLUSION

5.1. Aims of Thesis and Summary of Key Findings

The overall aims of this thesis were: (i) to address the lack of a knowledge synthesis examining the use of motor behavior concepts in balance control studies, (ii) enhance the understanding of APAs during a lower extremity Fitts' task, and how APAs are related to focus of attention; and (iii) investigate APAs and how they relate to focus of attention among populations who are known to have a high risk of falls such as older adults and people after stroke. This thesis document includes three manuscripts that explored motor behavior concepts that can be utilized to assess and modify postural adjustments. Specifically, the first study was a scoping review of the utilization of motor behavior concepts in studies related to balance control. Further, the second and third studies examined the effects of different foci of attention on APAs among young adults, older adults and people post-stroke when performing a lower extremity Fitts' task. In these two studies, I have focused on the relation between APAs and motor performance among different populations. Details of the differences between populations are discussed below.

In the first study a scoping review was conducted that examined the use of the CPF, Fitts' law and focus of attention among studies investigating balance control. The overall results showed that using the CPF is helpful to guide the progression of balance training programs. The CPF appears to be promising for balance training as it provides context for understanding the training variables as it relates the difficulty of the balance task to the skill level of the performer. The results of the review also showed that Fitts' law could be used as a method for controlling the difficulty of balance training exercises. Further, Fitts' law was used in different balance tasks, such as performing aiming movements while standing and controlling the COP to perform a goal-directed aiming task. Lastly, the results of the review also indicate that adopting an external focus of attention yields superior performance and learning of motor skills. Furthermore, in the review two points were identified in order to achieve highest advantages from adopting an external focus of attention: the task objective should also be external when adopting an external focus of attention; and, the more distant the point of focus when adopting an external focus of attention, the better the performance. However, a common limitation was found when reviewing the literature, which is that most previous studies looked at young people with no balance impairments. Further, there is scarcity in clinical trials that have used these motor behavior concepts for balance control studies.

In the second manuscript we investigated APAs among young and older adults when performing a lower extremity Fitts' task and the effects of different foci of attention on APAs and task variables. The overall findings were in line with previous research, as adopting an external focus of attention led to superior performance compared to an internal focus of attention. The superior performance was seen in both age groups as an external focus was associated with significantly shorter movement times, higher peak velocity of movement, shorter time to peak velocity and more accuracy when reaching towards target. Further, EMG results showed that an external focus of attention led to earlier onset of APAs and more efficient APA magnitude. We also found that the amplitude of the Fitts' task had a more prominent effect on motor performance and APAs, and the width of target did not have a significant effect on APAs. In regard to differences between the two age groups, the task used in our study was able to differentiate between them. It was shown that older adults exhibited less optimal performance in the task, as assessed by behavioral, kinematic and APA measures.

When examining the results of the second manuscript within the context of the CPF, it seems to be possible to identify an optimal challenge point for training individuals, such as older adults, to improve their APAs. The results of the study showed that there is a difference in the performance between young and older adults, which indicates that there is a difference in the optimal challenge point between these two populations. The difference in the optimal challenge point between the two age groups can be seen in their differences in movement planning as assessed by the duration of APAs. In other words, as amplitude increased (i.e., difficulty increased) the differences between the two groups became more pronounced. Therefore, when assessing APAs among older adults using longer amplitudes would be more indicative of APAs impairments then smaller movement amplitudes. Further, adopting an external focus of attention seemed to have altered the optimal challenge point for individuals. This alteration of the optimal challenge point can be seen in the results related to target endpoint variability (Figure 3-6). When participants adopted an internal focus their target endpoint variability was similar for amplitudes 40 cm and 60 cm. However, when adopting an external focus of attention a difference was present between the two aforementioned amplitudes. This difference suggests that an external focus of attention helps distinguish between the different levels of difficulty and thus promote performance by adequately identifying the optimal challenge point for the performer. Identifying an optimal challenge point in a task similar to our study would involve controlling the difficulty of the task (i.e., Fitts law), determining the skill level of the performer (i.e., older or young adult) and providing individuals with feedback that promote performance (i.e., an external focus of attention). Subsequently, the optimal challenge point would be the most difficult practice condition at which individuals can perform the task before performance deteriorates. Determining an optimal challenge point could also lead to identifying individuals who are in need of clinical intervention for improving their APAs, and subsequently, decrease their risk of falling.

In the third manuscript, we extend our investigation to people post-stroke. In this study we investigated the effects of different attentional foci on APAs when performing a lower extremity Fitts' task. The overall results were in line with previous research. When adopting an external focus of attention, individuals exhibited better performance as determined with behavioral, kinematic and APA measures. Similar to our previous study, we found that the amplitude of the Fitts' task had more effect on performance while the width of target had a smaller impact on performance. However, the effect of amplitude was only found to affect behavioral and kinematic measures but did not affect APA measures. Another finding in this study was that the patients' physical impairment level, assessed by CMSA-leg and –foot subscales, was closely related to the participants' performance. It was found that as the CMSA scores were higher, the better was the performance. This is in agreement with the CPF, which indicates that individuals with different skill level show differences in performance. It was also apparent that the task used in our study could differentiate between the skill levels of individuals, suggesting that an optimal challenge point can be identified for APA training. For example, in this study participants with CMSA-leg scores 6 and 7 had similar movement time, peak velocity, and duration of APAs. The lack of differences between the two groups with CMSA-leg scores (6 and 7) suggest that the difficulty of the task did not reach an optimal challenge point and thus performance was equal between these two groups.

When comparing the performance of young adults, older adults and people post-stroke, the task used in our study did show differences between these populations. Young adults showed better performance, as assessed by behavioral, kinematic and APA measures, than older adults. Further, older adults showed better performance than people post-stroke. The amplitude of the Fitts' task was shown to have a major effect on performance for all three populations. However, it did not affect APA findings for people post-stroke. As discussed in Chapter four, the lack of amplitude effect on APAs could be related to the nature of lower extremity reaching task and how Fitts' law does not take into account all factors related to the stepping movement (e.g., height of step). Moreover, it is possible that the lack of amplitude effect on APAs is attributed to participants compensating for the different amplitudes with a more rapid step (i.e., increased velocity). In fact, when examining the performance of people post-stroke the results indicate that participants did in fact increase their velocity with increased amplitude.

5.2. Clinical Implications

Several clinical implications can be inferred from the studies presented in this thesis. Motor behavior concepts are useful for designing training programs for balance control studies. The results of the scoping review indicated that the CPF is a theoretical framework that aids in designing motor training programs. Further, when interpreting the results of the second and third manuscripts, the CPF was beneficial for providing context of the findings related to the performance of individuals when performing the lower extremity Fitts' tasks. Also the Fitts' task that was utilized in our studies appears to be helpful in determining the optimal challenge point at which individuals are adequately challenged and performing the task. For example, by controlling the nominal difficulty of the task (i.e., Fitts' law parameters) and providing external focus of attention instructions to enhance motor performance.

The Fitts' task used in our studies can be used to distinguish individuals who have high impairment of APAs. Thus, using this task as a performance-based objective outcome measure of APAs and determining individuals who are in need of clinical intervention to decrease risk of falls. Fitts' law can be used to control the difficulty of motor tasks. Also, Fitts' law has the benefit of reducing the chances of a learning effect when performing the motor task as Fitts' law is resistant to learning (Schmidt & Lee, 2011). Fitts' law tasks can also provide clarity on the motor planning and motor execution processes among individuals. For example, in the second manuscript the results showed that the target amplitude had a more prominent effect on outcome measures than the width of the target. This finding suggests that participants may have adjusted their movement planning primarily based on movement amplitude. Further, when participants adopted an internal focus of attention there was no effect of target width on variability at movement endpoint. However, when movement planning was managed under an external focus of attention, increased target width led to a significant reduction in variability at target.

Adopting an external focus of attention improves lower extremity motor performance and APAs among young adults, older adults and people post-stroke. However, the results of the studies suggest that the benefits of adopting an external focus of attention may be different between populations. For example, in the second manuscript the results indicated that as amplitude increased, APAs onset occurred earlier (with external focus). Further, there was a significant interaction for focus of attention by age group. This finding indicated that as amplitude increased (i.e., difficulty increased) the difference between the two groups became more pronounced. As such, there was a disproportionate difference between the benefit of an external focus for young adults and older adults, as young adults benefited more when adopting an external focus. Moreover, in the third manuscript the results of APAs duration showed that participants with different CMSA-leg scores showed disproportionate differences between the benefits of an external focus compared to an internal focus. The results showed that participants with higher CMSA scores benefitted more when adopting an external focus compared to an internal focus.

In this thesis I have chosen to examine APAs given their importance and their link to risk of falling (Horak, 2006; Hyodo et al., 2012; Uemura, Yamada, Nagai, & Ichihashi, 2011). Further, previous research related to focus of attention studies did not investigate the relation between focus of attention and APAs. Given the potential benefit of investigating focus of attention as a tool for improving APAs, and the importance of identifying methods for modifying APAs, I have investigated the effects of different foci of attention when performing a lower extremity Fitts' task. Further, previous research utilizing a similar Fitts' task has suggested that, the lower extremity Fitts' task used in our studies may be used as a performance based outcome measure (Passmore et al., 2015). Investigating APAs is important especially that there is paucity in studies examining methods for improving APAs among older adults and people post-stroke (Aruin, 2016; Aruin, Kanekar, Lee, & Ganesan, 2015; Kanekar & Aruin, 2015; Silva et al., 2018). Lastly, it is necessary to identify methods for assessing and improving APAs, especially that previous research indicates that improving APAs decreases the risk of falls (Aruin, 2016; Aruin et al., 2015; Kanekar & Aruin, 2014a, 2014b, 2015; Kubicki, Mourey, & Bonnetblanc, 2015; Saito, Yamanaka, Kasahara, & Fukushima, 2014).

5.3. Future Directions

As mentioned in previous chapters, the majority of studies related balance control that have used the CPF, Fitts' law and focus of attention have included participants who do not have balance impairments (i.e., healthy young adults). Future research should include subjects who have balance impairments in order to provide recommendations that are applicable to such populations. Further, there is a limited umber of studies that have utilized these motor behavior concepts in clinical trials (e.g., RCTs). Future studies should consider utilizing these motor behavior concepts when designing clinical trial studies to better understand the impact of these concepts among clinical populations.

The results in our two experimental studies provide the groundwork for determining the challenge point at which older adults and people post-stroke are at a higher risk of falling and thus in need of clinical intervention. The task used in our studies can be used as a performance-based objective outcome measure of APAs. By utilizing higher movement amplitudes, APAs parameters show more pronounced differences between the different populations. Further, by establishing a point at which individuals are at higher risk of falling, the task in our study can serve as a useful tool for rehabilitation clinicians. Future research is warranted to investigate the use of the Fitts' task in our studies as a performance-based objective outcome measure of APAs.

Despite the number of studies suggesting the beneficial effects of adopting an external focus of attention for motor performance and learning, the mainstream use of this concept in clinical context has lagged behind. In a mixed methods design study, investigators conducted a study to investigate frequency of feedback versus instructions during physiotherapy sessions of people post stroke (Durham, Van Vliet, Badger, & Sackley, 2009). Further, the authors wanted to determine what types of feedback (internal or external foci) physiotherapists often use during therapy sessions with people post stroke. Durham et al. (2009) recruited eight physiotherapists and eight patients with stroke. The authors used video recordings of therapy sessions, interviews of both therapists and patients and questionnaires for therapists. The results showed that therapists used instructions during therapy ~87% of the time, even though previous studies suggest that feedback is more beneficial for people post stroke (Carr & Shepherd, 2003; van Vliet & Wulf, 2006). Furthermore, when examining the feedback statements used, ~96% of feedback statements promoted an internal focus of attention. A very similar study was also conducted and the authors reported that during gait rehabilitation of people post-stroke, 67% of statements were internally-focused, 22% were externally-focused and 11% were mixed focus (Johnson, Burridge, & Demain, 2013). The findings in these studies suggest that the clinical and community settings may benefit from utilizing an external focus of attention.

Due to the lack of uptake of motor behavior concepts in clinical settings it is important to ask how these concepts can be applied on a widespread basis? Scientific research produces large amounts of knowledge. This knowledge is vital for fields that provide services to clients. Healthcare and community settings that are up-to-date in their practice perform more effectively and efficiently (Ferlie, Fitzgerald, & Wood, 2000; Grol & Grimshaw, 2003; Straus, Tetroe, & Graham, 2013). However, as seen in the above examples related to focus of attention, the exponential growth in research is not automatically followed by an implementation of knowledge among stakeholders (Kristensen, Nymann, & Konradsen, 2016; Rangachari, Rissing, & Rethemeyer, 2013). In response to this issue, in recent years there has been a growing interest in implementation science and knowledge translation (KT) of research into practice.

Future efforts are needed to promote the uptake of utilizing an external focus of attention during the training of motor skills in clinical and community settings. There is scarcity in large-scale clinical trials that examine the beneficial effects of adopting an external focus of attention when performing balance control tasks. Future research is recommended to examine the use of an external focus of attention in applied clinical research. In order to facilitate implementing this concept, KT experts should be involved in clinical research utilizing motor behavior methodology. Also, stakeholders, such as clinicians, patients and organizations, should be consulted for clinical research. With the incorporation of the aforementioned recommendations, it is possible to rectify the lack in uptake of motor behavior concepts in clinical settings.

5.4. Limitations

There are a number of limitations present in the work presented in this thesis. First, it is unknown if the benefits observed (i.e., in terms motor performance and APAs) when adopting an external focus of attention are present only during the course of the study or if they last beyond the conclusion of the experiment. Although previous studies related to focus of attention have shown that benefits of adopting an external focus of attention are retained beyond the course of an experiment (Chiviacowsky, Wulf, & Wally, 2010; Wulf, Höß, & Prinz, 1998; Wulf, Shea, & Park, 2001; Wulf, Weigelt, Poulter, & McNevin, 2003), in our study retention of motor performance and APAs improvement was not investigated. Furthermore, older adults and people post-stroke who were recruited for our studies only represent a specific portion of these populations. Individuals recruited were required to have a high score (>45) on the Berg balance scale. Therefore, the results of these studies should be interpreted with caution. Future research is warranted to examine individuals with different balance levels in order to confirm in these findings can be extended to them.

5.5. Summary

To summarize, this thesis includes a comprehensive examination of three motor behavior concepts and how they are related to postural control among young adults, older adults and people post-stroke. Clinical implications related to the three motor behavior concepts are identified and how they can be used for better understanding of balance control and decreasing the risk of falls. Finally, future research recommendations are provided in order to reduce the apparent gap between basic sciences and clinical practice. The body of work as a whole contributes to the existing motor behavior and rehabilitation literature. The thesis includes a scoping review on the utilization of the CPF, Fitts' law and focus of attention in balance control studies. The review provides important observations related to the use of these motor behavior concepts in balance control studies. Further, the review provides recommendations for clinicians involved in balance training and suggestions for future research. The dissertation also establishes new avenues for investigation that have implications for fall prevention in older adults and people post-stroke. The results of the second and third manuscripts indicate that adopting an external focus of attention improves movement performance and APAs. Further, the task used in our studies can distinguish the performance between different populations. Lastly, we provide future research recommendations based on the findings obtained in the two studies.

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