Fall-risk Factors in Community-dwelling Ambulatory Individuals with Chronic Stroke.

BY

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BPT., Manipal Academy of Higher Education, India, 2018

THESIS

Submitted as partial fulfillment of the requirements for the degree of Master of Science in Rehabilitation Sciences in the Graduate College of University of Illinois at Chicago, 2020
Chicago, Illinois

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ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor, Dr. Tanvi Bhatt, for her expert guidance and support throughout my graduate education in the MS Rehabilitation Science program at the University of Illinois at Chicago. Her unwavering support and encouragement over the past two years kept me constantly engaged with my research. Her mentoring facilitated the development of new skills and knowledge that not only helped me in writing this thesis but will always play a significant role throughout my career. I would also like to thank my thesis committee, Dr. Alexander Aruin and Dr. Edward Wang, for their invaluable time, support, and encouragement towards this thesis.

My appreciation also extends to my laboratory colleagues for making my graduate degree a great learning experience and for helping me in data collection and analysis for the successful completion of my thesis. I would also like to thank them for the stimulating discussions, hard work completed together, and all of the fun we had in the past two years. In addition, I would like to take this opportunity to extend my gratitude to all of the study participants, as without their participation this thesis would not have been completed.

Lastly, I would like to acknowledge my parents, family, and friends who in spite of being thousands of miles away encouraged, supported, and believed in me for the successful completion of this thesis.

CONTRIBUTION OF AUTHORS

Chapter 1 provides a review of the literature that places my dissertation question in the context of the larger field and highlights the significance of my research question. Chapter 2 represents a manuscript which is under review (Gangwani R, Dusane S, Wang S, Kannan L, Wang E, Fung J, Bhatt T. Slip-fall predictors in community-dwelling, ambulatory individuals with stroke) for which I was the primary author. Shamali Dusane, Shuaijie Wang, and Lakshmi Kannan provided significant contribution in data collection and analysis. Shamali Dusane also helped in drafting and editing the manuscript. Dr. Edward Wang provided his expertise on the statistical analysis section of the manuscript. Dr. Joyce Fung and Dr. Tanvi Bhatt contributed significantly in experimental design, writing, and editing of the manuscript as well as funding the research. Chapter 3 represents another manuscript which is still under work. I primarily worked on the data collection and analysis along with the writing and editing of the manuscript with the help of Dr. Tanvi Bhatt. Louis DePasquale contributed significantly in research design and protocol development. I anticipate that this project will be continued in the laboratory after I leave to collect more data and this work will be published as part of a co-authored manuscript.

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LIST OF ABBREVIATIONS

PwCS: People with chronic stroke

BBS: Berg Balance Scale

TUG: Timed Up and Go

FMA: Fugl-Meyer Assessment

ABC: Activities Specific Balance Confidence Scale

CIQ: Community Integrity Questionnaire

SOT: Sensory Organization Test

PASE: Physical Activity Scale for the Elderly

ICF: International Classification of Functioning, Disability and Health

SST: Spring Scale Test

RIPPS: Repeated, incremental, predictable perturbation, reactive stepping

TBW: Total body weight

SUMMARY

Falls are a common complication post-stroke. Falls in individuals with stroke are multifactorial and are associated with a wide range of stroke-related impairments. Such associated impairments in conjunction with the challenging ambulatory environments predisposes people with stroke to fall-risk and may result in physical, psychosocial, and socioeconomic consequences, thereby effecting their quality of life. While there are several fall-risk prediction models to identify individuals with stroke at high risk of falls, there is a lack of comprehensive analysis of fall-risk factors. Most fall-risk prediction models consider only physical factors such as balance, sensorimotor impairment, and muscle strength, but do not take into account psychosocial factors, such as fear of falling, as fall-risk factors. Furthermore, few models include only clinical measures and do not consider instrumented measures, which are objective in nature for fall-risk prediction. In addition to assessing intrinsic fall-risk factors that predispose an individual to fall on experiencing a perturbation, it is also essential to assess their responses to overcome the perturbation and prevent a fall. Considering the complex nature of falls and their consequences, there is a need to determine the most sensitive fall-risk factors that can help in identifying individuals with stroke at high fall-risk.

The main purpose of this thesis was to perform a multifactorial analysis of fall-risk factors to determine the most sensitive factors and measures to predict fall-risk in community-dwelling ambulatory individuals with chronic stroke. This purpose was achieved by including clinical and instrumented measures assessing various fall-risk factors from each of the domains of the International Classification of Functioning, Disability and Health (ICF) framework. Such a framework enables us to identify fall-risk factors at different levels of the ICF and help us develop feasible fall-prevention paradigms focusing on those domains. In addition to assessing intrinsic

fall-risk factors focusing on volitional balance control, we also aimed to assess reactive balance control by assessing stepping responses crucial for fall prevention. Thus, we utilized the Spring Scale Test (SST) described by DePasquale and Toscano which can induce waist-pull perturbations to assess and quantify reactive stepping response measures. The SST has been determined as a reliable, valid, and feasible reactive balance assessment tool. We conducted a pilot study focusing on assessing reactive balance using the SST to determine whether there is a correlation between these stepping measures and fall history in individuals with stroke.

The first study aimed to perform a multifactorial analysis comprising of various clinical and instrumented measures in order to assess fall-risk factors from each of the domains of the ICF. We conducted statistical analyses on the data collected from fifty-six individuals with stroke to determine the sensitivity and accuracy of measures from each of the domains of the ICF in predicting laboratory-induced slip fall-risk. The results indicated a model comprising of measures from the body structure and function domain (dynamic gait stability and hip extensor strength) and activity limitation domain (Timed Up and Go) as sensitive predictors of laboratory-induced slip-related fall-risk. The data is presented in Chapter II.

While the first study focused on intrinsic fall-risk factors, primarily focusing on volitional balance control, the second study is a pilot study done on seven individuals with stroke to assess reactive balance in individuals with stroke by administering the Spring Scale Test to assess stepping responses crucial for fall prevention. The results indicated that stepping response measures correlated with fall history in individuals with stroke. The study also included a secondary analysis to determine the correlation between stepping response measures and various fall-risk factors such as balance, mobility, and sensorimotor impairment to determine whether fall-risk factors influence stepping response measures. The data is presented in Chapter III.

CHAPTER I

INTRODUCTION

1.1 Background

Falls are a common and a serious complication post-stroke (Simpson et al., 2011; Weerdesteyn et al., 2008). Studies have reported fall incidence between 37% and 73% in individuals with acute stroke (<6 months) (Forster & Young, 1995; Mackintosh et al., 2006; Nyberg & Gustafson, 1995). The risk of falls continues in the chronic stroke stage with a higher fall incidence in people with chronic stoke (PwCS) compared to their age- and gender-matched controls (Simpson et al., 2011). Most falls in PwCS commonly occur during community ambulation, especially on exposure to external environmental perturbations such as slips and trips (Schmid et al., 2013; Yates et al., 2002). Such falls not only result in physical consequences such as soft tissue injuries and fractures but are also a leading cause of psychosocial consequences such as depression and fear of falling (Hyndman et al., 2002; Schmid & Rittman, 2009). In addition, falls and their associated consequences can cause socioeconomic distress, thereby further affecting a person's quality of life (Stevens et al., 2006). Considering the high fall incidence in PwCS and its serious complications, it is crucial to develop fall-assessment protocols that can best predict fall-risk and identify those at high risk of falling.

1.2 Statement of the problem

Falls in individuals with stroke might be a result of impairment in postural control which is required to maintain body orientation and stability (Pérennou, 2006; Weerdesteyn et al., 2008). A conceptual model has been developed to understand postural control and includes a complex interaction of various systems such as musculoskeletal system, sensory systems, and neuromuscular system that work together to maintain body orientation and stability (Horak, 2006; Sousa et al., 2012). However, the neurological insult caused by stroke can result in a detrimental effect on these systems causing impaired balance, sensorimotor deficits, muscle weakness, and impaired gait pattern, which predisposes people with stroke to high fall-risk (Kiyota et al., 2011; Mansfield et al., 2013; Tasseel-Ponche et al., 2015). In addition, postural control is also required to correctly predict, detect, and encode perturbations as well as respond to those perturbations (compensatory stepping) in an effective manner to prevent a loss of balance (Dakin & Bolton, 2018; Lakhani, 2010). Previous literature has suggested that fall-risk can arise from various intrinsic factors such as poor volitional balance control, muscle weakness, sensorimotor impairment, and fear of falling in addition to impaired reactive balance control needed in response to perturbations (Mansfield et al., 2015; Schinkel-Ivy et al., 2016).

1.3 Significance of the problem

Considering that fall-risk is multifactorial in PwCS, it is crucial to determine factors that can best predict fall-risk and differentiate fallers from non-fallers. While there are several studies on fall-risk prediction in PwCS (Nyberg & Gustafson, 1997; Walsh et al., 2016), there is a lack of comprehensive analysis of all these factors that might predispose them to falls. For example, studies have been done that assess only physical fall-risk factors such as balance, functional mobility, and muscle strength, but do not take into account psychosocial factors such as fear of falling that might predispose PwCS to fall-risk (Knorr et al., 2010; Tinetti et al., 1990). Additionally, most studies use only clinical fall-risk measures which might be limited considering their ceiling or floor effects, especially in community-dwelling PwCS, and do not take into account instrumented measures which might quantify and provide an objective fall-risk assessment

(Lamola et al., 2015; Visser et al., 2008). Moreover, studies that assess the reactive balance component involve exposing PwCS to perturbations to examine stepping responses. However, these perturbations are induced mechanically in the laboratory settings using motorized treadmills and waist-pulls which might limit its translation in clinical settings (Mille et al., 2003; Salot et al., 2016). Thus, it is crucial to not only identify fall-risk factors and the measures to assess them, but it is also important that the sensitive fall-risk prediction measures can be utilized in clinical settings and are feasible enough to be incorporated in fall-risk assessment protocols to identify PwCS at fall-risk. Further, identification of fall-risk predictors can facilitate development of appropriate fall prevention strategies and those identified at risk of falls can be provided specific interventions to improve fall-risk factors.

1.4 Purpose of the study

Thus, the purpose of this thesis was to perform a multifactorial analysis of various fall-risk factors and determine factors that can best predict fall-risk in PwCS. The first study included a wide range of clinical and instrumented measures focusing on intrinsic fall-risk factors from the three domains of the International Classification of Functioning, Disability and Health (ICF) to assess various fall-risk factors predisposing PwCS to falls and to determine the most sensitive fall-risk prediction model. While the first study primarily assessed volitional balance control, the second study aimed to assess reactive balance control which is crucial to regain balance following a perturbation. The second study included a novel fall-risk assessment tool called the Spring Scale Test (SST) that quantifies reactive stepping response measures to assess reactive balance control in PwCS. The identification of sensitive intrinsic fall-risk factors and reactive stepping response measures can facilitate identification of those at risk of falls and assist to develop specific interventions targeting the identified risk factors. Hence, the overall purpose of the thesis was split into two aims:

Aim 1: The purpose of the first experiment was to assess various fall-risk factors from each of the domains of ICF and determine a model that can best predict laboratory-induced slip related fall-risk in PwCS.

Hypothesis 1: We hypothesized that factors from each of the domains of the ICF will be sensitive predictors of laboratory induced slip-related fall-risk in PwCS.

Aim 2: The purpose of the second experiment was to determine the correlation between reactive stepping response measures derived from the SST with fall history in PwCS. A sub-analysis was done to determine the influence of stroke-related impairments on reactive stepping response measures.

Hypothesis 2: We hypothesized that reactive stepping response measures derived from manual waist-pull perturbations induced by SST will correlate with fall history in PwCS.

1.5 Organization of the thesis

The thesis is organized into three chapters. Chapter I provided an overview of the background, purpose, and significance of the study. Chapters II and III test the aims of the two experiments; they describe the background, methods, results, discussion, and conclusion along with the clinical implications for each experiment.

CHAPTER II

Slip-fall predictors in community-dwelling, ambulatory stroke survivors.

The data presented in this chapter is currently under review in the Journal of Neurologic Physical Therapy.

2.1 Introduction

Falls among people with chronic stroke (PwCS) are a serious threat, especially when they achieve community ambulation and are exposed to external environmental disturbances, such as slips or trips (Salot et al., 2016; Schmid et al., 2013; Weerdesteyn et al., 2008). Slips are associated with a higher fall incidence than trips, as recovery from slips can be more challenging (Patel & Bhatt, 2018). Furthermore, slip-falls can result in physical, psychosocial, and socioeconomic distress (Belgen et al., 2006; Haddad et al., 2019; Schmid & Rittman, 2009; Stevens et al., 2006). Thus, there is a need to identify PwCS at fall-risk. However, considering the varying severity of stroke-specific impairments and the multifactorial nature of falls, it is challenging to identify measures that best predict fall-risk among PwCS (Campbell & Matthews, 2010).

Several measures have been established as fall-risk predictors for PwCS. Common clinical measures include Berg Balance Scale (BBS), Timed Up and Go (TUG), Fugl-Meyer Assessment (FMA), and muscle strength, which assess various intrinsic/volitional fall-risk factors such as balance, functional mobility, sensorimotor and strength impairment, respectively (Beninato et al., 2009; Sawacha et al., 2013). While several studies demonstrated that such measures can predict fall-risk (Mackintosh et al., 2006; Simpson et al., 2011), few studies found no difference in performance in these measures between fallers and non-fallers (Brauer et al., 2000; Harris et al., 2005). Moreover, individuals who performed well were still at risk for falling, possibly due to the ceiling effect, especially among high-functioning PwCS (Balasubramanian, 2015; Mancini & Horak, 2010; Patterson et al., 2017). Furthermore, these measures assess an individual's performance on discrete tasks which may not be representative of real-life fall scenarios. Additionally, they do not directly assess recovery responses needed to prevent an impending fall. Thus, it is essential to further determine whether such impairments can identify PwCS at fall-risk.

Additionally, it has been suggested that a comprehensive model beyond a physical model could better predict fall-risk among PwCS (Baetens et al, 2011; Wei et al, 2017). Psychosocial factors assessed using the Activities-specific Balance Confidence (ABC) scale and Community Integration Questionnaire (CIQ) have been identified as fall-risk predictors (Baetens et al., 2011; Pang & Eng, 2008). Studies indicate that fall history might induce fear of falling, resulting in self-imposed restriction of physical activity and declining functional capacity, further predisposing individuals to fall-risk (Denkinger et al, 2015; Schoene et al., 2019). However, few studies demonstrated a discrepancy between self-efficacy scores and fall-risk (Hadjistavropoulos et al., 2011; Lajoie & Gallagher, 2004). Considering that self-efficacy refers to beliefs about one's own ability as well as functional limitations (Tinetti et al., 1990), there might be a mismatch between one's own perception to their real balance and gait impairments. Thus, limiting the contribution of fear of falling for fall-risk prediction.

Due to the limitations of above-mentioned measures, studies have used objective measures for fall-risk prediction (Bower et al., 2019; Kanekar & Aruin, 2013). For example, the Sensory Organization Test (SOT) is a form of computerized posturography that quantifies postural sway under various sensory conditions (Oliveira et al., 2011; Wallmann, 2001). SOT composite scores are known to predict fall-risk in PwCS (de Oliveira et al., 2008). However, as most falls occur during walking, assessing walking stability might provide better fall prediction than posturography during stance. Over the years, a conceptual framework has been developed that humans must simultaneously control their center of mass (COM) position and velocity (COM motion state) to prevent a fall. This gave rise to the biomechanical measure of dynamic gait stability which measures the distance from a person's instantaneous COM motion state to their limits of stability (Patton et al., 1999). Although dynamic gait stability is a significant fall-risk predictor in healthy older adults, it is unclear whether it can potentially identify slip-fall-risk among PwCS (Bhatt et al., 2011).

Although several studies have examined fall-risk predictors under one of the International Classification of Functioning, Disability and Health (ICF) domains, limited studies included predictors across all domains (Beninato et al., 2009; Huang et al., 2016). Additionally, previous studies consider retrospective fall history to classify fallers and non-fallers which could induce inaccuracies in fall-risk prediction due to recall bias or misunderstanding a fall event. Secondly, falls can include both slips and trips and results may be biased depending on the fall type prevalent in the study. To overcome these barriers, researchers have now successfully induced realistic slip and trip falls in laboratory settings. Previous literature indicates that real-life like perturbations can be simulated in safe, controlled laboratory environment, thus providing an opportunity to validate causal-effect relationship of falls and offer a diagnostic and prognostic tool to detect and prevent real-life falls albeit in a safe and controlled laboratory settings (Bhatt et al., 2011; Wang et al., 2019). Considering the impact of slip-falls, this study focused on examining fall-risk predictors in response to realistic, laboratory-induced slip-falls. Further, to conduct a stochastic study to systematically and comprehensively examine slip-related fall-risk factors in PwCS, there would be a need to collect enough number of real-life slip falls in community-dwelling ambulatory individuals with stroke, resulting in a longitudinal study design. However, longitudinal studies take substantial amount of time and are prone to significant attrition of sample size. Further, falls collected in real life might not be accurately and sensitively reported due to lack of understanding a fall event, recall bias and inability to differentiate or recall fall type such as a slip or trip. Thus, the purpose of this study was to examine fall-risk predictors across the ICF domains to obtain a model that can best predict fall-risk in PwCS in a safe laboratory environment.

2.2 Methods

2.2.1 Participants

Sixty-one community-dwelling individuals with chronic (stroke onset > 6 months) hemiparetic stroke capable of independently walking 7m (length of the instrumented walkway) with no complaints of musculoskeletal or cardiovascular conditions, systemic disorders, or any other neurological conditions were included in this study. Participants with low bone density (T score < -2), cognitive deficits (score of ≤ 26/30 on the Montreal Cognitive Assessment Scale), or speech deficits (aphasia score of ≥71/100 on the Mississippi Aphasia Screening Test) were excluded. Following the screening, clinical measures were performed, and one-year fall history was recorded. Of the sixty-one participants, five had missing data, resulting in fifty-six individuals being included for data analysis. This study was approved by the Institutional Review Board of the University of Illinois at Chicago, and written informed consent was obtained from all participants prior to their enrollment.

2.2.2 Data collection

Data was collected by two trained research assistants, responsible for performing the following assessments and conducting the laboratory slip-test sessions. Following measures were collected from each of the domains of the ICF.

Body structure and function domain

Dynamic gait stability assessment

The dynamic gait stability assessment considers both COM position and its instantaneous velocity. The regular walking trial at a self-selected speed immediately prior to the unannounced slip was analyzed to obtain dynamic gait stability. Helen Hayes marker set with 30 full-body reflective markers were attached to anatomical landmarks to assess stability. Marker coordinates were recorded using an 8-camera motion capture system (Motion Analysis Corporation, Santa Rosa, California). Marker displacement data was low-pass filtered at optimal cut-off frequencies ranging from 4.5–9 Hz using a fourth-order Butterworth filter. Force plate data, harness load cell data, and trigger-release onset signals were collected at 600 Hz using a 64-channel, 16-bit analog to digital converter. The ground reaction force and motion data were time synchronized using a trigger signal during data collection. The vertical ground reaction force data was used to determine the gait events (step touchdown and lift-off) and verified from foot kinematic data collected via 3D motion analysis. The motion analysis data was used to compute the absolute COM position using a 12-segment body representation model. The instantaneous COM velocity was calculated by taking the time derivative of the COM position trajectory. The COM position was expressed relative to the heel of the base of support (BOS), normalized by the participant's foot length, whereas velocity was expressed relative to the BOS, normalized by a dimensionless fraction of $\sqrt{g \times h}$ (g=gravitational acceleration, h=participant's height). Thus, dynamic gait stability was measured as the shortest distance between the instantaneous COM motion state and previously predicted computational limits of the feasible stability region (Pai & Iqbal, 1999). Stability values > 0 indicate decreased likelihood of backward balance loss whereas stability values < 0 indicate greater likelihood of backward balance loss (Yang et al., 2008).

<u>Sensory Organization Test (SOT)</u>

SOT assessed postural sway under progressively challenging sensory conditions. Two 20-second trials were performed for each condition. A composite score ranging from 0 (higher sway) to 100 (no sway) was calculated as the weighted average for all conditions (Cohen et al., 1996; Ford-Smith et al., 1995).

Fugl-Meyer Assessment scale for lower extremity (FMA-LE)

FMA-LE is a stroke-specific, performance-based index that assesses sensorimotor impairment (reflexes, movement, coordination, joint range of motion, and joint pain). Each item was scored on a 3-point scale with scores ranging from 0 to 86 (Gladstone et al., 2002; Sanford et al., 1993).

Strength assessment

Maximum voluntary isometric force-generating capacity was assessed for paretic lower limb muscles using Biodex (Kluding & Gajewski, 2009). Participants performed three trials for each movement with rest periods between trials. They were instructed to exert their maximum effort and were verbally encouraged throughout the assessment.

Activities-specific Balance Confidence (ABC) Scale

ABC scale rates a participant's confidence level from 0% to 100% in 16 functional activities of daily living. The self-rated scores for each activity are averaged to yield the mean ABC score. Higher scores represent higher balance confidence (Botner et al., 2005; Powell & Myers, 1995).

Activity limitation domain

Berg Balance Scale (BBS)

BBS is a measure comprising of 14 functional tasks. Each task was scored on a scale from zero to four based on participants' ability to meet task-specific goals for a maximum possible score of 56 (Blum & Korner-Bitensky, 2008; Stevenson, 2001).

Timed Up-and-Go (TUG)

TUG assesses functional mobility. Participants were instructed to stand up from a chair, walk for three meters, turn around, return to the chair, and sit back down "as quickly and as safely as possible." The score was the time taken in seconds to complete the test (Podsiadlo & Richardson, 1991; Shumway-Cook et al., 2000).

Participation restriction domain

Physical Activity Scale for the Elderly (PASE)

PASE measures self-reported physical activity and determines the frequency and duration spent on leisure, household, and occupational activities over a seven-day period. Higher PASE scores represent greater physical activity with scores ranging from 0 to 400 or more (Logan et al., 2013; Washburn et al.,1993).

Community Integration Questionnaire (CIQ)

CIQ consists of 15 items regarding participants' activities from a home, social, and community integration perspective. The basis for scoring is primarily the frequency of activity performance with secondary weightage given to whether activities were performed alone, with someone's help, or completely by someone else. Scoring ranges between 0 to 29 points (Corrigan & Deming, 1995; Willer et al., 1994).

Contextual factors

The ICF consists of contextual factors (environmental and personal). This study included fall history as a personal contextual factor. A previous fall experience can affect a person's participation level, thereby affecting activities and, in turn, body structure and function (Liu, 2017). One-year fall history was recorded using a self-reported questionnaire. A fall was defined as an event where the participant unintentionally came to rest on the ground or another lower level (Zecevic et al., 2006).

Slip simulation and falls reproduction

The slip was induced by a low-friction, moveable platform using a computer-controlled release mechanism on a 7m instrumented walkway (Figure 1). Previous evidence suggests laboratory-induced slip-fall incidences are similar for both paretic and non-paretic limbs. However, as stability is lower during paretic slips than non-paretic slips (Kajrolkar & Bhatt, 2016), the former could potentially be more harmful. Thus, a novel paretic slip was induced to assess and validate various fall-risk measures. Upon touchdown of the paretic foot, the platform unlocked and would slide a maximum slip distance of 45cm. Participants wore athletic shoes, orthoses (if any), and a full body safety harness throughout the experiment. The harness was attached to a ceiling mount with a load-cell which recorded the weight supported by the harness. Participants were told to walk at their self-selected speed, and baseline walking trials were collected to ensure they consistently landed on the moveable plate with their paretic limb. Following baseline walking trials, participants were informed that a slip might occur at any time and they should try to recover their balance and continue walking. A forward slip under the paretic limb was induced with no warning or practice, thereby simulating realistic slips while walking. Slip outcomes were classified as either a fall or recovery based on the force data recorded by the load cell. A fall was identified when the load cell force exceeded 30% of the participant's body weight and was verified via visual inspection of all video records (Yang & Pai, 2011).

2.2.3 Data analysis

Data for all variables was summarized using descriptive statistics (means ± standard deviations) and compared using student t-tests between fallers and non-fallers. Univariate logistic regression was performed to identify predictors of laboratory-induced slip-falls. Sensitivity, specificity, and overall accuracy were calculated for each variable. Subsequently, variables with a significance level of < 0.3 were included for further analysis in the multivariable regression model (Bhatt et al., 2011; Heinze & Dunkler, 2017). A backward stepwise logistic regression was performed to determine a model that could best predict laboratory-induced slip-falls. Odds ratio was also calculated. The area under the curve (AUC) was found using the Receiver Operating Curve (ROC) for variables as well as for the best predictive model. Statistical significance was established at an alpha level of 0.05 throughout the study. All statistical analyses were performed using SPSS 25.0 software (IBM Corp., Armonk, NY).

2.3 Results

Of the fifty-six included participants, 42.85% (24) fell and 57.15% (32) successfully recovered from the slip. There was no effect of age, height, and weight of study participants on the perturbation outcome. TUG (p=0.01) and hip extensor strength (p=0.04) were significant variables indicating that fallers walked slower (high TUG scores) and had less strength compared to non-fallers. Dynamic gait stability was also significantly different between fallers and non-fallers (p=0.01) (**Table 1**).

Based on the Youden Index, the cut-off score determined for dynamic stability was -0.15 and for TUG was 13 seconds. The cut-off score for hip extensor strength was determined at 106 Nm. Additionally, ROC results show the AUC for TUG was 0.701 and 0.713 for hip extensor strength, whereas the AUC was 0.782 for dynamic gait stability, indicating a higher prediction capacity of dynamic gait stability (**Table 2**).

Dynamic gait stability, TUG, hip extensor strength, FMA, and ABC scores were included for the multivariable analysis. The analysis resulted in a model with TUG, hip extensor strength, and dynamic gait stability as significant predictors of falls with a sensitivity of 75%, specificity of 79.2%, an overall prediction accuracy of 77.3% and AUC at 0.863 (**Table 3, Figure 2**).

2.4 Discussion

Our study findings indicate a model comprising of dynamic gait stability, hip extensor strength and TUG score was a significant predictor of laboratory-induced slip-fall-risk in PwCS.

Fall-risk predictors in the body structure and function domain

Dynamic gait stability was a predictor of laboratory-induced slip-falls in PwCS. Individuals' balance and mobility is determined by their ability to maintain stability by controlling their COM movement relative to their BOS (Lugade et al., 2011; Pai & Patton, 1997). Previous studies indicated that controlling the COM plays a crucial role in maintaining stability (Devetak et al., 2019; Iqbal, 2011). Our study findings showed fallers had more negative dynamic gait stabilities than non-fallers. This is consistent with findings from previous literature which demonstrated reduced dynamic gait stability as one of the causative factors of falls (Yang et al., 2009). Thus, negative dynamic gait stability not only increases fall-risk but might also make recovery from slips more difficult. Our study results provide preliminary evidence that dynamic gait stability could predict slip-fall-risk in PwCS.

In our study, strength was measured by assessing peak isometric force of paretic lower limb muscles (hip and knee flexors and extensors, ankle plantar flexors and dorsiflexors). However, only hip extensor muscle strength was a significant predictor of laboratory-induced slip-fall-risk in PwCS. Our results are consistent with previous studies indicating that hip extensor strength is an effective measure of determining falls (Palmer et al., 2015; Pavol et al., 2002). Previous literature on laboratory-induced falls have indicated that in addition to poor stability, reduced limb support or unintended hip descent can result in a fall (Pavol & Pai, 2007; Yang et al., 2009). Such unintended hip descent can be caused by inadequate concentric work by the hip extensors (Pavol & Pai, 2007). Thus, weak paretic hip extensor strength can result in descent of the slipping (paretic) limb, thereby further limiting the ability of the paretic limb to weight bear while the non-paretic limb executes a compensatory step to reestablish the BOS, recover stability, and regain limb support to prevent a fall.

SOT was unable to predict laboratory-induced slip-fall-risk, most likely due to its limited ability to assess balance in stance. Given the ambulatory nature of our study population, it can be argued that stance perturbations may be less challenging or insufficient for testing fall-resisting skills. Furthermore, the nature and intensity of the perturbations caused by SOT might not be comparable to realistic slip perturbations, thereby limiting its sensitivity in fall-risk prediction.

Also, most of the studies done using SOT as a fall-risk predictor considered retrospective fall history. Hence, it is unclear whether SOT can predict immediate or future fall-risk.

Another variable, FMA, was not able to differentiate fallers from non-fallers. One reason could be because FMA rates an individual on discrete motor tasks and does not assess responses required to prevent a fall. Also, irrespective of the sensorimotor impairment level, our study population of PwCS may have adapted to their impairments and developed compensatory strategies to cautiously navigate their environment. Similarly, ABC, was not able to predict laboratory-induced slip-fall-risk. About half of the study participants fell upon experiencing a slip, however, the mean ABC score for the fallers group was 76.87%, indicating a ceiling effect for ABC. Thus, there may be a mismatch between individuals' self-perception of their own abilities and their functional mobility, balance, and gait impairment.

Fall-risk predictors in the activity limitation domain

TUG was a significant predictor of laboratory-induced slip-falls in PwCS. Such a result can be attributed to the fact that tasks performed during TUG such as sit-to-stand, walking, and turning mimic daily activities that increase real-life fall-risk. Additionally, our results indicate that fallers had a higher TUG score (slow gait speed) compared to non-fallers who had lower TUG score. Previous literature has indicated that a slower walking speed is associated with decreased stability against a backward loss of balance (Bhatt et al., 2005). Thus, participants who took more time to complete the TUG were at higher risk of fall on exposure to the laboratory-induced slip. Moreover, TUG is an easy test to perform, requiring minimal space and resources to conduct the test and can be used in clinical settings to identify PwCS at fall-risk.

Another variable BBS was not able to predict laboratory-induced slip-fall-risk. Prior studies suggested BBS was a significant predictor of falls during the acute and post-acute stroke periods, therefore BBS might have limited sensitivity to predict laboratory-induced slip-fall-risk in PwCS (Knorr et al., 2010). Based on previous studies which showed a BBS score above 45 to be indicative of reduced fall-risk (Doğan et al., 2011), there should have been comparatively less falls in our study as participants had a mean BBS score of 48.41. However, despite the higher scores, about half of individuals fell, indicating that BBS might not accurately predict falls in PwCS.

Fall-risk predictors in the participation restriction domain

PASE and CIQ were not predictors of laboratory-induced slip-fall-risk. PASE requires recall of physical activity events over a seven-day period, which might contribute to recall bias. Furthermore, PASE comprises duration and frequency of activities such as gardening, wall papering, and lawn work which may not be performed by PwCS. In addition to memory or recall bias, study participants may have felt the need to provide socially desirable answers which might further limit the sensitivity of these measures.

Contextual factors as fall-risk predictors

Fall history could not predict laboratory-induced slip-fall-risk, most likely owing to the recall bias associated with correctly remembering previous fall types (slip or trip). Prior studies which suggested fall history was a predictor of falls mostly considered recurrent fall history (Ashburn et al., 2008; Mackintosh et al., 2006); however, most study participants reported a single fall history, which might not be sufficient to classify individuals as “fallers”.

Fall-risk predictors from multivariate regression analysis

The multivariate analysis determined a model comprising of dynamic gait stability, hip extensor strength, and TUG to predict laboratory-induced slip-fall-risk. Thus, indicating that measures from the body structure and function and activity limitation domain of the ICF can be sensitive predictors of laboratory-induced fall-risk. Additionally, the cut-off scores determined for these measures are consistent with the previous literature. The cut-off score determined for dynamic stability was -0.15, indicating that PwCS with more negative values are at higher fall-risk. Our cut-off score is similar to a previous study in older adults indicating that older adults with dynamic gait stability cut-off score of less than -0.15 have 69% sensitivity of fall-risk (Bhatt et al., 2011). Similarly, the cut-off score for TUG in our study was 13 seconds, indicating that PwCS taking more than 13 seconds to complete the test were at an increased fall-risk. Similar cut-off scores for TUG were reported in a previous study demonstrating the sensitivity of TUG in fall prediction was almost 50% when people with CS took more than 14 seconds in the TUG test (Scale & Talking, 2006). Thus, given the range and complex interaction of factors that contribute to falls in PwCS, it is essential to assess all aspects of fall-risk. The ICF provides an ideal framework for organizing these various aspects, and our study results show that a comprehensive analysis provides a sensitive fall-risk prediction model.

Clinical applications and limitations

Study findings indicate measures from the ICF assessing various fall-risk factors might provide a sensitive model for laboratory-induced slip-fall-risk prediction and can be implemented to identify PwCS at slip-fall-risk. Assessment of dynamic gait stability, TUG, and hip extensor strength should be included for fall-risk prediction. The latter two can easily be assessed clinically, and, with the advent of commercially available cost-effective wearable sensors, dynamic stability could be easily computed using a single sensor affixed to the sacrum (Yang & Pai, 2014). These measures can help identify problems at different ICF levels, and those identified as having slip-fall-risk could undergo training protocols to prevent falls.

However, the study has few limitations. As the study included ambulatory PwCS, these results cannot be generalized to individuals in the acute stage with limited ability to ambulate. Furthermore, although balance is a crucial factor for preventing falls, BBS was not a significant predictor of fall-risk. Future studies should consider including the mini-BESTest (a measure assessing reactive balance), as it could be a sensitive predictor of fall-risk (Potter & Brandfass, 2015). Further, for this study, participants wore their own comfortable shoes which might have an impact on their ability to control the moveable platform, thereby affecting slip intensity.

2.5 Conclusion

A model comprising of dynamic gait stability, TUG, and hip extensor strength can be used by healthcare professionals to predict slip-fall-risk in PwCS. Future fall-risk assessment models should involve a comprehensive analysis of risk factors using various measures within the ICF to provide better prediction accuracy and sensitivity.

Table I

Sample demographics organized by slip outcome (fall vs recovery during the laboratory test) with their respective means, standard deviations (SD), and statistical significance based on t-test results.

	Fall (N=22)	Recovery (N=24)	
Variables	**Mean (SD)**	**Mean (SD)**	**p value**
Age (y)	57.16 (10.33)	59.12 (10.27)	0.49
Weight (kg)	98.88 (19.24)	93.16 (16.35)	0.32
Height (m)	1.71 (0.10)	1.73 (0.10)	0.22
TUG (s)	17.78 (8.44)	12.79 (4.48)	0.007
Stability	-0.19 (0.05)	-0.12 (0.09)	0.006
BBS (out of 56)	48.41 (5.92)	49.33 (4.82)	0.53
FMA	63.66 (10.82)	73.87 (7.75)	0.09
Fall history (%)	66.0 (48)	47.0 (50)	0.34
ABC (%)	76.87 (16.39)	81.69 (14.99)	0.26
CIQ	16.63 (4.45)	16.75 (4.31)	0.92
PASE	95.13 (61.54)	80.04 (45.48)	0.30
SOT (out of 100)	75.20 (5.93)	73.57 (10.39)	0.50
Hip flexors (Nm)	27.53 (19.25)	28.75 (13.28)	0.51
Hip extensors (Nm)	91.82 (32.11)	120.73 (45.93)	0.02
Knee flexors (Nm)	46.31 (21.59)	40.53 (22.33)	0.38
Knee extensors (Nm)	54.96 (23.66)	62.30 (26.61)	0.33
Dorsiflexors (Nm)	21.81 (13.38)	22.08 (15.99)	0.95
Plantarflexors (Nm)	36.29 (26.26)	36.67 (23.88)	0.96

Table II

The sensitivity, specificity, overall prediction accuracy, and significance from univariate regression analyses with area under curve (AUC) derived from Receiver Operating Curve (ROC).

Variable	Sensitivity	95% CI	Specificity	95% CI	Overall accuracy	p value	AUC	95%CI
TUG (s)	41.72	27-67	81.81	51-87	64.91	0.01	0.701	0.564-0.838
Stability	58.34	40-70	80.62	56-90	70.93	0.01	0.782	0.657-0.907
SOT (out of 100)	47.61	27-67	65.25	48-82	56.82	0.49	0.476	0.326-0.626
FMA	29.22	37-77	81.84	58-88	59.64	0.10	0.609	0.452-0.766
BBS (out of 56)	8.30	10-27	97.01	80-94	59.67	0.73	0.542	0.387-0.696
Fall history	66.71	47-85	52.23	33-71	57.96	0.33	0.564	0.413-0.716
ABC (%)	16.73	22-62	90.91	71-93	59.65	0.26	0.595	0.437-0.754
CIQ	28.65	11-45	73.92	58-88	57.92	0.92	0.536	0.384-0.688
PASE	42.91	22-62	78.34	67-99	61.44	0.46	0.570	0.409-0.731
Hip flexors (Nm)	5.32	16-54	96.04	49-87	56.85	0.51	0.499	0.322-0.676
Hip extensors (Nm)	60.05	55-89	75.02	30-70	68.27	0.04	0.713	0.556-0.869
Knee flexors (Nm)	15.08	10-44	89.37	60-90	58.36	0.37	0.414	0.250-0.578
Knee extensors (Nm)	19.02	27-67	78.64	30-70	53.11	0.32	0.549	0.385-0.714
Dorsiflexors (Nm)	21.11	6-36	70.02	55-85	57.18	0.94	0.502	0.334-0.669
Plantarflexors (Nm)	44.42	25-63	57.91	38-76	57.45	0.95	0.522	0.350-0.694

Table III

The components of the predictive models using multivariable logistic regression.

Independent variables	p value	Odds ratio (95% CI)	Cut-off	Sensitivity	Specificity (%)	Overall Accuracy (%)	AUC	95% CI
Stability	0.011	2.64 (1.34-4.28)	-0.156	75.0	79.2	77.3	0.863	0.754-0.971
TUG (sec)	0.058	2.35 (1.46-3.88)	13					
Hip extensor strength (Nm)	0.084	2.12 (1.58-3.64)	106					

Figure 1

Figure 1 is a schematic diagram of the experimental set-up with the approximate position of the participant at touchdown of the slipping limb. The unfilled circles indicate the positions of reflective markers on the body segments and the moveable platform. The I-beam and safety harness are much higher than shown (9m above the ground). Shown are the 2 sliding devices that were placed side-by-side to induce bilateral slips. The moveable platforms were locked and embedded in the 7m walkway. Once released, the moveable platforms were released to slide a maximum distance of 45cms.

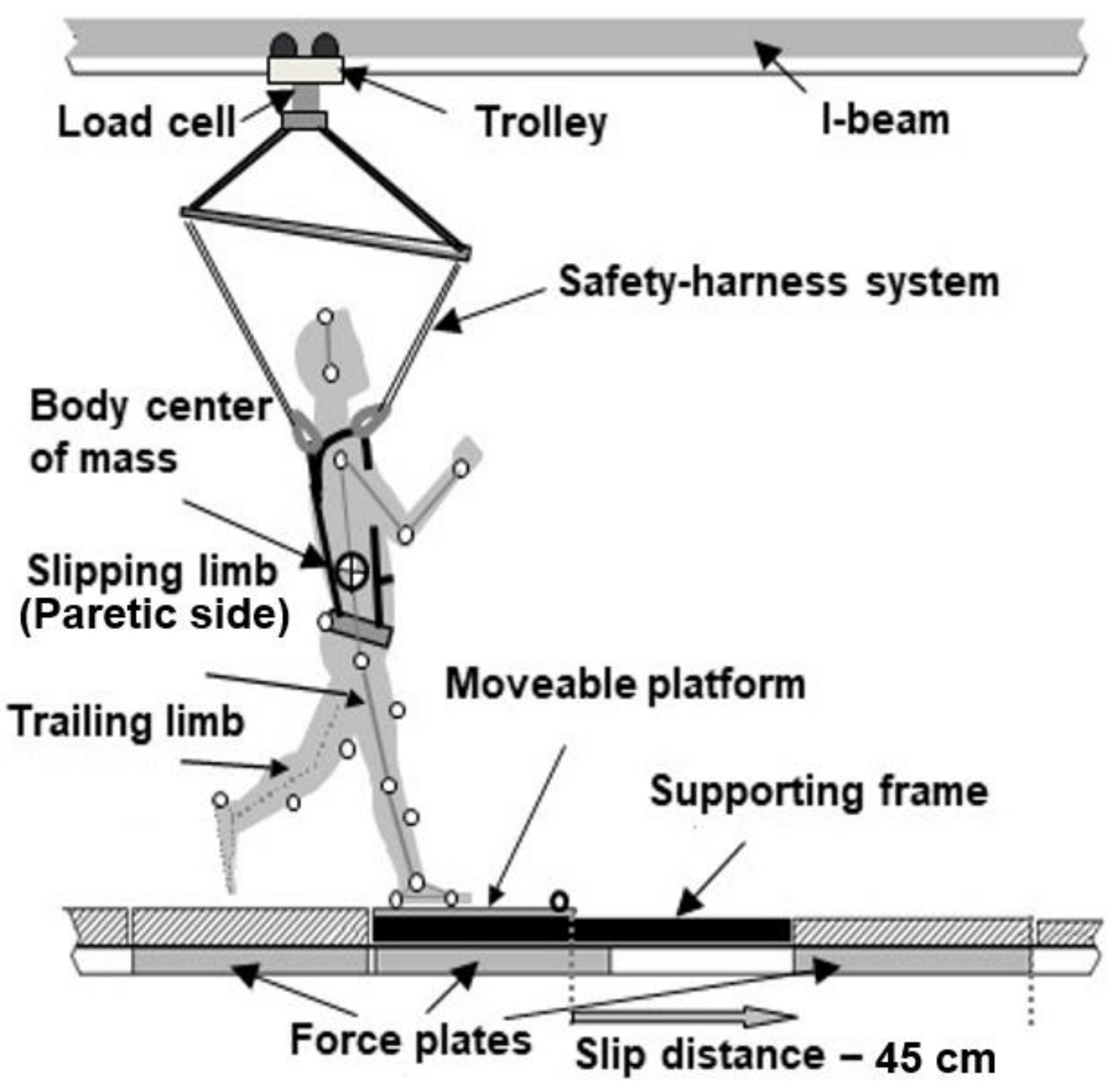
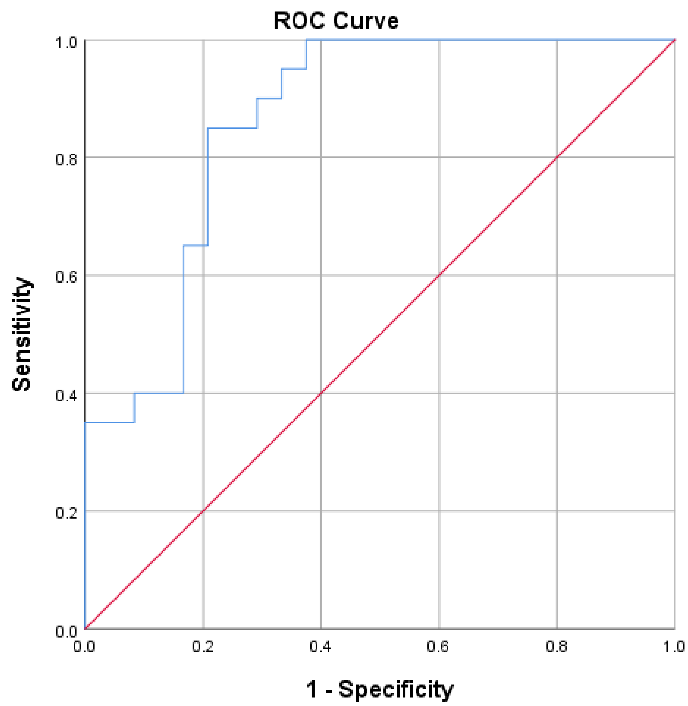


Figure 2

Figure 2 shows the area under the curve (AUC) of the model (blue line) comprising of variables dynamic gait stability, TUG and hip extensor strength, found using the ROC curve.



CHAPTER III

Reactive stepping responses mediated by predictable manual waist-pull perturbations are associated with fall history in community-dwelling individuals with stroke.

3.1 Introduction

Falls are a common health concern in individuals with stroke throughout their post-stroke lifespan (Batchelor, Mackintosh, Said, & Hill, 2012; Weerdesteyn et al., 2008). Falls in people with chronic stroke (PwCS) result in several physical and psychosocial consequences and are a common cause of socioeconomic distress, thereby impacting quality of life (Hyndman et al., 2002; Simpson et al., 2011). Considering the risk of falls and its consequences in PwCS, it is essential to differentiate fallers from non-fallers and to identify those at high fall-risk.

While several-fall risk factors have been identified that predispose PwCS to the risk of falls, most studies assess only volitional risk-factors, including the study described in Chapter II of this thesis (Chin, Wang, Ong, Lee, & Kong, 2013; Nyberg & Gustafson, 1997; Whitney, Dutt-Mazumder, Peterson, & Krishnan, 2019). In addition to these identified factors, another crucial factor that determines whether an individual will fall is based on their ability to react to a loss of balance. On encountering a perturbation, it is essential to execute a recovery response, such as initiating a compensatory step in an effective and timely manner in order to prevent a fall (Lakhani et al., 2011; Maki & McIlroy, 2006). However, previous literature indicates deficits in reactive balance control in PwCS. This might be attributed to the asymmetric nature of the injury which can challenge the choice of stepping limb, thereby resulting in a markedly delayed stepping response (Kajrolkar et al., 2014; Mansfield et al., 2012). Additionally, PwCS demonstrate ineffective stepping responses due to inadequate foot clearance resulting from an inability to lift the paretic limb high enough to clear the ground thereby limiting the ability of paretic limb to execute a recovery step. Furthermore, an inability to weight bear on the paretic limb could result in an impaired execution of a step with the non-paretic limb (Mansfield et al., 2011; Salot et al., 2016). Such deficits result in impaired execution of recovery responses, fundamental to stabilize the body following a perturbation, resulting in a heightened fall-risk in PwCS.

Despite the importance of reactive balance control for fall prevention, it is less frequently assessed in clinical settings, possibly influenced by outcome measures commonly used for fall risk assessment. For example, performance-based tests like the Berg Balance Scale (BBS) and Timed Up and Go (TUG) are widely used and accepted tools for fall-risk assessment in PwCS. However, these measures assess only volitional balance control and do not comprise of components to assess reactive balance needed for fall prevention. Therefore, these example measures do not provide insights on underlying deficits in fall-resisting skills. A clinical performance-based measure which incorporates postural reactions to perturbations to assess reactive balance is the Balance Evaluation Systems Test (BESTest). The tester observes the individual’s response to a push force and grades it ordinally. Considering such a subjective nature of grading postural responses, more objective measures of postural responses to perturbations have been described. Researchers have developed methods that induce standardized perturbations to assess reactive balance. Studies have demonstrated the use of motorized treadmills and waist-pulls to induce perturbations (Joshi et al., 2018; Patel & Bhatt, 2015; Salot et al., 2016). Such perturbations displace the center of mass (COM) outside the base of support (BOS) similar to real-life perturbations, thereby eliciting reactive recovery stepping responses to regain balance in PwCS (Osman et al., 2019). Thus, studies have utilized mechanical perturbations as a tool for assessing reactive balance to predict fall-risk (Nevisipour et al., 2019; Patel & Bhatt, 2016; Shirota et al., 2017). However, such motorized treadmills and waist-pulls for reactive balance assessment have several limitations. Firstly, considering the high cost and limited portability of such motorized systems, it might be difficult for such tools to be translated to clinical settings. Additionally, clinical settings might have limited space and lack set-up for a motorized system, thereby further limiting the wide use of such reactive balance assessment tools. Thus, there is a need to determine a clinically feasible reactive balance assessment tool in PwCS.

A perturbation-based reactive balance assessment tool called the Spring Scale Test (SST) has been developed in older adults. The SST is a tether-release, repeated, incremental, predictable perturbation, reactive stepping (RIPPS) fall assessment and intervention tool which measures and quantifies protective stepping responses as a percent of total body weight (%TBW). Such a tool quantifies effective limits of both rear and forward stepping by inducing anterior and posterior waist-pull perturbations, respectively, for the purpose of fall-risk assessment. An initial study utilizing SST by DePasquale demonstrated that SST is a reliable and valid tool for predicting fall history in the older adult population (DePasquale & Toscano, 2009). However, there is lack of evidence in determining whether such a reactive balance assessment tool can be utilized in PwCS and if the outcome measures derived from SST can associate with fall-risk in PwCS.

Considering the above-mentioned limitations of clinical fall-risk measures and perturbation-based devices, such as a treadmill for reactive balance assessment, as well as the lack of evidence of SST as reactive balance assessment measure in PwCS, this study aimed to determine whether outcome measures derived from the SST can correlate with fall history in PwCS. Any association, if proven, will provide preliminary evidence on utilizing SST as a simple and feasible tool in clinical settings for reactive balance assessment and to differentiate fallers from non-fallers among PwCS. Additionally, the study included a sub-analysis aimed to determine whether fall-risk factors such as balance, mobility, and sensorimotor impairments assessed using various clinical fall-risk measures will correlate with reactive stepping response measures in PwCS. Such information will provide further insight on the influence of various other fall-risk factors on stepping responses and help us determine whether improving other fall-risk factors can enhance reactive stepping responses.

3.2 Methods:

3.2.1 Recruitment

PwCS were recruited through email and advertisements via study flyers at the local stroke support groups, neurologist and physician offices, and the university hospital.

3.2.2 Participants

Seven individuals with chronic (stroke onset > 6 months) hemiparetic stroke capable of standing independently and with no complaints of acute or chronic musculoskeletal or cardiovascular conditions, systemic disorders, or any other neurological conditions were included in this study. Participants with low bone density (T score < -2), cognitive deficits (score of ≤ 26/30 on the Montreal Cognitive Assessment Scale), speech deficits (aphasia score of ≥ 71/100 on the Mississippi Aphasia Screening Test), or weighing more than 200 lbs were excluded. After the initial screening, clinical measures were performed, and two-year fall history was recorded. Recall for fall incidents over a two-year period was considered in an attempt to include individuals beyond acute and subacute stages of fall recovery and to ensure a high possibility of recording real-life falls over a long period of time, thereby further increasing the sensitivity of fall history as a study variable. Fall was defined as an event where "any balance disturbance resulted in a person unintentionally coming to rest on the ground or any other lower surface." This study was approved by the Institutional Review Board of the University of Illinois at Chicago, and written informed consent was obtained from all participants prior to their study enrollment.

3.2.3 Data collection

Data was collected by two trained physical therapists/research assistants who were responsible for performing all of the assessments and conducting the SST.

Assessment protocol

The participants underwent several clinical assessment measures as follows:

Timed Up and Go test (TUG)

The Timed Up and Go test (TUG) is a test used to assess functional mobility. Participants were instructed to stand up from a chair, walk for three meters, turn around, return to the chair, and sit back down “as quickly and as safely as possible.” The score was the time taken to complete the test in seconds (Podsiadlo & Richardson, 1991; Shumway-Cook et al., 2000).

Berg Balance Scale (BBS)

Berg Balance Scale (BBS) is a balance measure comprising 14 functional tasks. Each task was scored on a scale from zero to four, for a maximum possible score of 56, based on participants’ ability to meet task-specific goals (Berg et al., 1995).

Fugl Meyer Assessment (FMA)

The Fugl Meyer Assessment (FMA) scale is a stroke-specific, performance-based index used to assess sensorimotor impairment. It comprises 17 items measuring reflexes, movement, coordination, joint range of motion, and joint pain. Each item was scored on a three-point scale with scores ranging from 0 to 86 (Sanford et al., 1993).

Spring Scale Test (SST)

The spring scale is a pocket-sized eight-inch linear spring scale with a 26-pound (12-kilogram) capacity, capable of quantifying manual waist-pull forces in one-pound increments with a zero set point turn dial calibration capacity (Pelouze/Pelstar LLC, Product of Pelstar; Bridgeview, IL). Calibration accuracy of the linear spring scale-measuring instrument is achieved through suspension of a five-pound weight before the start of the test. The SST comprises of a padded five-inch-wide belt which is secured around the participant's waist. The spring scale is attached to the padded belt on one end and the other end is held by the examiner. A four-foot tether strap is secured at waist level to both the examiner and the participant for safety purposes while enabling unrestricted responses to the waist-pull perturbations. A waist-pull force is applied in the sagittal plane with the scale held parallel to the ground.

The SST belt was secured at the subject's waist, without over-tightening the waist belt, to allow easy transition from anterior to posterior testing without unfastening the waist belt closures. The waist-pull perturbation was delivered with the spring scale device attached to the belt around the subject's waist. The examiner assumed a stable stance in close proximity to the participant, grasping the spring scale pull handle and maintaining the spring scale instrument and participant's feet in clear view. Depending upon leg length and height, the participant stood approximately three feet from a compliant support surface, such as a bed, sofa, padded treatment table, or other suitable support surface, to hold onto if needed.

SST consists of round of loading and unloading starting from one-pound waist-pull force and was increased by an additional one-pound in subsequent rounds of coupled loading and unloading. Loading waist-pull forces were administered in a gentle, slow, continuous, predictable, and accommodative fashion. Unloading occurred suddenly and without warning in a random manner at the discretion of the examiner within a subjective five-second window following successful foot flat accommodation to loading waist-pull forces. Examiners repeatedly provided verbal cues to participants during testing regarding waist-pull force magnitude and direction. Participants were continuously reminded to withstand as much waist-pull loading force as possible maintaining heel/sole foot contact with floor support surface and to step when necessary, with the fewest steps required to maintain their balance. The second examiner guarded the participant. In addition, there were compliant surfaces placed posteriorly and laterally to the participant at arm's distance to hold on to while trying to regain their balance, if required. The test was initially done with anterior waist-pull perturbations followed by posterior waist-pull perturbations. Each round of testing assessed balance reactions in response to a) the spring scale loading force and b) the spring scale unloading force. The protective reactive stepping responses thus elicited were measured as a percentage of total body weight (%TBW) force.

Outcome measures derived from SST:

1. **% total body weight or stepping threshold:** The maximum waist-pull force at which the participant demonstrates initial onset of stepping response during unloading, reported as a percentage of the person's total body weight (%TBW)
2. **% total body weight limit:** The maximum amount of waist-pull force sustained within an effective protective stepping response limit (three step limit criteria) irrespective of loading/unloading, at which the participant demonstrates failure.

3.2.4 Data Analysis

For the purposes of this paper, fallers and non-fallers based on their two-year fall history were denoted a bivariate numerical value of 1 or 0, respectively. Spearman's correlations were performed to determine the correlation between the outcome measures derived from both anterior and posterior SST (rear and forward stepping threshold and rear and forward stepping limit %TBW) with previous fall history. Additionally, means of threshold and limit %TBW were calculated for fallers and non-fallers for both anterior and posterior SST. Correlation was also performed between the clinical fall-risk measures such as the BBS, TUG, FMA, and the SST outcome measures to determine whether the scores obtained in clinical fall-risk measures are associated with performance in the SST.

3.3 Results

Our study results indicate that the mean anterior (rear step) stepping threshold for fallers is 5.83 %TBW whereas for non-fallers it is 7.32 %TBW. Similarly, the mean anterior (rear step) limit %TBW for fallers 8.13 %TBW whereas for non-fallers it is 10.37 %TBW. The mean posterior (forward step) stepping threshold for fallers is 6 %TBW whereas for non-fallers is 7.05%TBW. Similarly, the mean posterior (forward step) limit 8.7 %TBW for fallers is %TBW and for non-fallers is 8.5 %TBW. Thus, indicating that fallers had a lower stepping threshold and limit %TBW compared to non-fallers.

Fall history correlated with anterior (rear step) stepping threshold [r=-0.866, p=0.012] and limit %TBW [r=-0.801, p=0.030]. The correlation is almost significant with posterior (forward step) stepping threshold [r=-0.722, p=0.052], but no correlation between fall history and posterior (forward step) limit %TBW [r=-0.289, p=0.530] was found, thus indicating that anterior direction (rear stepping) measures correlate more with fall history compared to posterior direction (forward stepping) measures.

Our study results also indicate a correlation between outcome measures derived from SST and clinical outcome measures (BBS, TUG, and FMA). Anterior (rear step) stepping threshold correlated with BBS (r=0.829, p=0.021) and FMA (r=0.844, p=0.017). Similarly, anterior (rear stepping) limit %TBW also correlated with BBS (r=0.791, p=0.034) and FMA (r=0.787, p=0.036). Posterior (forward step) stepping threshold correlated with TUG (r=-0.893, p=0.007) and FMA (r=0.918, p=0.004).

3.4 Discussion

Our study results indicate that SST outcome measures correlated with fall history in PwCS, thereby providing preliminary evidence that SST can be utilized to differentiate fallers from non-fallers in PwCS. The results also indicated that fallers had a lower stepping threshold and limit %TBW compared to non-fallers (Inness et al., 2014; Mille et al., 2003). Further, the SST outcome measures correlated with clinical measures assessing various fall-risk factors such as balance, mobility, and sensorimotor impairment, therefore providing evidence that improvement in these fall-risk factors can improve reactive stepping responses needed for fall prevention.

This study determined stepping threshold as the %TBW in which an individual first initiates a stepping response in reaction to a waist-pull perturbation. Our study results are consistent with previous literature indicating that fallers had a lower stepping threshold compared to non-fallers, thereby indicating that fallers may not be able tolerate a greater waist-pull perturbation and thus initiate a stepping response to regain balance. Such a lower stepping threshold could be attributed to several reasons. Considering the stroke associated sensorimotor impairment in PwCS and the application of predictable but sudden waist-pull perturbations in our study, fallers might not have had enough time or strength to generate the muscle torque needed to maintain the foot-in-place strategy, therefore requiring a step to regain balance and prevent a fall. Further, considering the unilateral nature of stroke, PwCS demonstrate weight-bearing asymmetry with more weight distributed to the non-paretic side. Such an asymmetry has been shown to be a cause of postural instability (de Kam et al., 2016; de Kam et al., 2017), especially in the sagittal plane in which the waist-pull perturbations were induced. Such an instability might have resulted in fallers initiating a stepping response to regain balance. Moreover, studies have also indicated that individuals who have had a previous fall experience might initiate a step irrespective of the perturbation intensity due to fear of falling (Maki, 1997; Maki & McIlroy, 1997). Thus, fallers might have taken a step at a lower waist-pull force based on their previous fall experience.

Our results also indicate that fallers exhibit a lower limit %TBW compared to non-fallers. This demonstrates that fallers reach a point of failure at lower %TBW compared to non-fallers. Our results described limit %TBW as a point of failure in which study participants took three or more steps to regain balance. Studies have indicated that PwCS demonstrate an impaired ability to take a long compensatory step needed to prevent a fall and thereby resort to a multiple stepping response to regain balance (Lakhani et al., 2011; Salot et al., 2016). Such a multiple stepping response is common because of an inefficient first step characterized by a reduced step length which leads to a need of taking additional steps to maintain the base of support. Previous studies have also demonstrated that a multiple stepping response is indicative of fall-risk in PwCS (de Kam et al., 2018; Schinkel-Ivy et al., 2016). Additionally, studies have indicated that fear of falling may result in taking some unnecessary steps. Thus, PwCS may have taken some more steps to regain balance and thereby reached their limit %TBW.

Additionally, our study results also indicated a directional bias similar to that found in a previous study in older adults (DePasquale & Toscano, 2009), suggesting that anterior direction (rear stepping) measures correlate more with fall history compared to posterior direction (forward stepping) measures. This is similar to studies indicating that recovery from backward balance loss is more difficult than recovery from a forward balance loss (Patel & Bhatt, 2018). This might be due to several possible reasons. Firstly, visual information needed to regain balance might be higher on posterior waist-pull perturbations which induces forward stepping compared to rear stepping induced by anterior waist-pull perturbation. Thus, making anterior waist-pull perturbations more difficult to recover from and resulting in rear stepping measures correlating more with falls. Further, the trunk excursion needed to regain balance from backward balance loss (rear stepping) is more difficult than forward balance loss (forward stepping), thereby further proving that rear stepping measures have a better association with falls.

Our study results also indicate that SST derived outcome measures correlate with clinical measures assessing balance, mobility, and sensorimotor impairment. For example, anterior (rear step) stepping threshold and limit %TBW correlated with BBS assessing balance and FMA assessing sensorimotor impairments. Similarly, posterior (forward step) stepping threshold correlated with FMA and TUG. This indicates that balance deficits, poor functional mobility, and sensorimotor impairments play a role in recovery stepping responses essential for fall-prevention. Thus, our results indicate that training paradigms focusing on improving these fall-risk factors will also result in improving reactive stepping responses and thereby prevent or reduce fall-risk in PwCS.

Study limitations:

This study was done on community dwelling, ambulatory PwCS. For that reason, these results cannot be generalized to people with stroke in acute stages or with limited ability to ambulate. Moreover, the findings reported in this study based upon waist-pull perturbations which evoke both anterior and posterior stepping response may not be generalized to other forms of fall-provoking circumstances, such as slips and trips. Additionally, the present study restricted its analyses to observational measures, however, future studies should include electromyography to get a better understanding of reactive stepping responses in PwCS.

3.5 Conclusion

Our study results provide preliminary evidence that quantifiable reactive stepping response measures derived from the SST can be utilized to differentiate fallers from non-fallers in PwCS. Future studies are needed with a larger sample size and in individuals with stroke in various stroke stages to further determine the feasibility of such a reactive balance assessment tool in the stroke population.

Table IV

Correlation between outcome measures derived from the SST with fall history in PwCS.

	Stepping threshold (%TBW)	**Limit %TBW**
Rear stepping	-0.866*	-0.801*
Forward stepping	-0.722	-0.289

* Indicates value significant at $p<0.05$

Table V

Correlation between outcome measures derived from the SST and clinical fall-risk measures Berg Balance Scale (BBS), Timed Up and Go (TUG), and Fugl Meyer Assessment (FMA).

	Berg Balance Scale	**Timed Up and Go**	**Fugl Meyer Assessment**
Anterior (rear step) stepping threshold	0.829*	-0.750	0.844*
Anterior (rear step) limit %TBW	0.791*	-0.640	0.787*
Posterior (forward step) stepping threshold	0.671	-0.893**	0.918**
Posterior (forward step) limit %TBW	0.450	-0.357	0.257

** Indicate significance at $p<0.005$

*Indicate significance at $p<0.05$

Figure 3

Figure 3 demonstrates the Spring Scale Test (SST) anterior direction (rear stepping) and posterior direction (forward stepping) testing set up with one end of the spring scale attached to the participant's waist and the other end held by the examiner. A tether strap is secured via a belt at waist-level to both the participant and the examiner for participant safety.

Conclusion and Future directions

As falls in PwCS are multifactorial in nature and vary with the severity of stroke-associated symptoms, individuals with chronic stroke are at risk of falls, despite achieving community ambulation. Thus, this study performed a multifactorial analysis of fall-risk factors assessing both volitional and reactive balance to determine factors or measures that can best identify PwCS at fall-risk. The first study focused on measures assessing intrinsic fall-risk factors primarily assessing volitional balance. These measures were derived from the various domains of the ICF as the ICF provides a systematic and holistic approach of assessment. The study predicted variables such as dynamic gait stability, TUG and hip extensor strength as predictors of slip-related fall-risk in community dwelling PwCS indicating that variables from the body structure and function domain as well as the activity limitation domain can better predict fall-risk. The second study assessed, and quantified reactive stepping response measures using the SST and demonstrated a correlation between rear stepping %TBW and rear stepping limit %TBW with fall history in PwCS. Thus, our study indicated that assessment of both intrinsic fall-risk factors assessing volitional balance and reactive stepping responses is crucial for identifying PwCS at fall-risk. Future fall-risk assessment models performed by health care professionals in the clinical settings should involve a comprehensive analysis of fall-risk factors assessing both volitional (dynamic gait stability, TUG and hip extensor strength) and reactive balance (reactive stepping responses). Our study focused on high-functioning community-dwelling individuals with chronic stroke. Thus, studies should be done in low-functioning or individuals in the acute stroke stage to determine whether these predictors can be used as early predictors of fall-risk. Further, longitudinal studies can be performed to determine the predictive capacity of these fall-risk measures in predicting real-life prospective falls.

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VITA

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EDUCATION

University of Illinois at Chicago *Chicago, IL*
Masters Student, Rehabilitation Sciences, GPA: 4.00/4.00 *2018 - 2020*

Kasturba Medical College, Mangalore (Manipal University) *Mangalore, India*
Bachelor in Physiotherapy, GPA: 4.00/4.00 (As evaluated by WES) *2013-2018*

RESEARCH EXPERIENCE

University of Illinois at Chicago *Chicago, IL*
Research Assistant (CogMoBal Laboratory) *Fall 2018 – Current*

Perturbation training for enhancing stability and limb support control for fall-risk reduction among stroke survivors
National Institutes of Health (NIH), 2016-2021
PI: Dr. Tanvi Bhatt
Role: Research personnel responsible for recruitment, scheduling, assisting in lab screening and training stroke participants

INTERNSHIP & PROJECTS

Kasturba Medical College *Mangalore, India*
Internship Project *Aug 2017- Feb 2018*
Conducted a study to find the normative values of Modified Harvard Step test in healthy population

Kasturba Medical College *Mangalore, India*
Internship Rotations *Aug 2017- Feb 2018*
Completed 6 months mandatory internship in various neurological, orthopedic, cardiorespiratory pediatric and geriatric department as well as in intensive care units

HONORS AND AWARDS

Lillian Torrance scholarship, *University of Illinois at Chicago* *Spring 2019*
BOT tuition waiver, *University of Illinois at Chicago* *Fall 2018*
Best outgoing student in BPT, Kasturba Medical College *March 2018*

Jeena Memorial Gold Medal for Outstanding Academic Performance *March 2018*
AHS Achievement Award, *University of Illinois at Chicago* *Fall 2020*

POSTER PRESENTATIONS

Gangwani Rachana. Effect of Virtual Reality on hand rehabilitation in stroke. 2017, Physiocon, Mangalore, India

Gangwani. R, Dusane. S, Bhatt. T. Slip-fall risk predictors in community dwelling ambulatory stroke survivors. Society for Neuroscience (Oct 19^{th}-23^{rd})

Gangwani. R, Dusane. S, Bhatt. T. Slip-fall risk predictors in community dwelling ambulatory stroke survivors. AHS Research Day, 2019.

PUBLICATIONS

Gangwani R, Dusane S, Wang S, Kannan L, Wang E, Fung J, Bhatt T. Fall risk predictors in community dwelling ambulatory stroke survivors. Journal of Neurological Physical Therapy (in review)

Wang Y, **Gangwani R,** Kannan L, Schenone A, Wang E, Bhatt T. Can smartphone derived steps data predict fall-risk in healthy older adults? Frontier in Sports and Active Living (in print)

PROFESSIONAL ORGANIZATION

Member of the Society of Neuroscience *July, 2019 - Present*

PHYSICAL THERAPY LICENSURE

Working on getting licensure for state of Indiana.