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Effects of Stance Symmetry on Perturbation-Induced Protective Stepping in Persons Poststroke and Controls

April 2, 2016

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A dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Signature page

Abstract

Problem Statement: Stepping is a common strategy after a perturbation. Stroke survivors display a predilection for stepping with non-paretic leg. Insight into induced stepping between stroke survivors and age-matched control may guide our understanding for reactive postural control training post stroke.

Purpose: To investigate the difference in perturbation-induced stepping between chronic stroke survivors and age-matched controls at three phases of the stepping response: preparation, execution, and landing and association with clinical outcome measures.

Procedure: Twenty-one community-dwelling chronic stroke survivors (mean age 59y/o ±13yrs) and 17 age- and gender-matched controls (mean age 54.4y/o ±17yrs) completed this study. Clinical measures of gait, balance, range, sensation, and motor control were assessed. A mechanical weight drop of 10% body weight (BW) was used to create the anterior waist pull perturbation during three stance symmetry positions: equal stance (EQ) and two asymmetrical stance (70% BW on dominant leg and 70% BW on nondominant leg). Ten perturbation trials plus two catch trials at 2% BW were given in a standard randomly order at the three stance positions. Kinematic and kinetic data was collected for perturbation steps.

Results: The asymmetrical trials resulted in two types of stepping response, steps with the leg bearing 70% BW (loaded steps – LS) and steps with the leg that had 30% BW (unloaded steps – ULS). All subjects initiated steps more often with their unloaded leg (ULS) in the asymmetrical stance trials. In the stroke group the ULS increased paretic leg stepping compared to EQ (p=0.001) and LS (p=0.001). The stroke group had significantly earlier APA onset with both non-paretic leg (p=0.003) and paretic leg (p=0.028), took significantly more steps with paretic (p=0.01) and non-paretic (p=0.07), shorter step length (paretic, p=0.025 and non-paretic p=0.003), and less change in momentum at landing with paretic leg (p=0.01) compared to controls.

Conclusion: Reacting to a perturbation is more challenging for chronic stroke survivors than age- and gender-matched control subjects in the preparation, execution, and landing phase of the stepping response regardless of the leg used. Perturbation training should include stepping with both non-paretic and paretic leg.

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Chapter 1: Introduction

Introduction to the Chapter

Chapter 1 provides a brief description of the falls and balance deficits in the poststroke population and introduces the concept of stepping as a dynamic balance response to a large perturbation. This chapter also includes the study purpose, research question, and definition of terms.

Overview of the Problem

Falls in persons poststroke occur more frequently than falls in older adults.[1] In community-dwelling stroke survivors the percentage of fallers one year poststroke range from 40-70%, with 21-57% for repeat fallers.[2] Numerous factors such as motor and sensory deficits, mental decline, incontinence, gait deficits, poor balance, and a fear of falling have been identified as risk factors in persons poststroke.[3-5] One might conclude that falls are more common in individuals poststroke who present with more severe impairments and limitations in balance and mobility, however research has not supported this relationship.[3,6-8] In fact one study suggests that a higher number of impairments results in decreased mobility and therefore lower risk for falls.[3]

Impaired postural control is a common element for fall risk in both the elderly and persons poststroke. This is commonly assessed by examining a person's ability to maintain a static posture, move within a posture (dynamic or proactive balance), and recover upright control after an external perturbation (reactive balance). Current standing balance assessment tools used with persons poststroke are limited, and many of these balance assessment tools utilize a feet-in-place strategy such as ankle / hip strategies or volitional stepping to assess balance.[9-12]

Sixty percent of individuals poststroke are ambulatory and are especially vulnerable to falls given their neuromuscular impairments.[13] Studies on balance in persons poststroke have focused on static and proactive balance control with relatively few recent studies dealing with reactive balance recovery.[14-17] The literature on protective stepping in older adults has grown over the last decade, and clinical practice is beginning to utilize protective stepping as a strategy for balance recovery and preventing falls in older adults.[18] Little is known about protective stepping in persons poststroke. Preliminary studies have shown that persons post–acute stroke are able to execute protective steps and have a preference for stepping with their less involved leg.[19,20] Our recently published study identified similarities and differences between voluntary and perturbation-induced stepping in chronic stroke survivors and raised some questions about the effect of weight bearing on induced steps and directions of perturbation.[21] Systematic identification of the preparation, execution, and landing phase of protective stepping in stroke survivors could provide useful information for assessment and treatment intervention of reactive control and fall risk.

Relevance and Significance

Past research has highlighted the importance of stepping as a common strategy for dynamic balance recovery in everyday situations.[22] This ability to rapidly move the feet to catch the body is an important strategy for fall prevention. Older adults are reported to initiate protective stepping earlier and with smaller perturbations than younger individuals.[23] When older adults utilize protective stepping they tend to take more multiple steps, with steps that are shorter, and with lower clearance.[24-26] These step characteristics in older adults may be a consequence of diminished sensorimotor and neuromusculoskeletal functioning. Similar decrements are seen in persons poststroke, yet information on protective stepping responses in this population is limited.

Protective stepping is one aspect of reactive balance control that has been studied in the non-stroke population. These studies have highlighted the importance of stepping as a common strategy for dynamic balance recovery in everyday situations.[22] The ability to rapidly move the feet to catch one's body is an important strategy for fall prevention. The literature on protective stepping in older adults has grown, and clinical practice is beginning to utilize protective stepping as a strategy for balance recovery and preventing falls in older adults.[18] Ambulatory individuals poststroke are especially vulnerable to falls given their balance, mobility, and motor recruitment impairments, yet little is known about protective stepping in persons poststroke.

Protective stepping response in persons poststroke was investigated. Two reports were case studies, and two were retrospective chart reviews all using subjects from an inpatient rehabilitation setting.[19,20,27] In all four reports, many of the subjects required assistance to prevent falls during the perturbation trials and had a preference (56%) for stepping with the less-involved leg. In our recently published study on induced protective stepping in chronic stroke survivors, all 10 participants were able to maintain their balance with multiple steps.[21] Eight of the ten subjects used both the involved and less-involved leg for induced compensatory stepping, while only two subjects always stepped with their less-involved leg. This indicates there may be significant difference between stepping strategies in chronic versus acute stroke survivors.

In the pilot study for this dissertation, there was a significant difference in the mean number of steps taken at 10% body weight perturbation (Appendix A) but no difference in the induced protective step characteristics (onset, clearance, duration) between 14 chronic stroke survivors and nine age- and gender-matched controls. This may indicate that other factors could be involved in maintaining upright control beyond execution of a protective step. Stabilizing balance with one step requires precisely stopping the movement of the center of mass (COM) relative to the base of support (BOS). For healthy adults, a reduced margin of stability at foot contact and at maximum knee flexion was reported between older vs. younger adults and between older multiple vs. single steppers, suggesting instability in the landing phase in older adults.[28] The ability to utilize stepping as a mechanism for upright control after a perturbation poststroke may therefore be related to the landing phase of stepping.

Appropriate weight shift and stabilization on the stance leg is needed prior to lift off of the stepping leg. This postural preparation is different in voluntary stepping and induced stepping in the elderly, young adults, and persons poststroke.[21,23,29] Movement of the COM and center of pressure (COP) prior to step onset has been shown to be different between involved and less-involved legs in persons poststroke but not different between limbs in healthy controls during voluntary stepping.[30] Asymmetrical standing posture is common poststroke and may affect this preparatory response in gait initiation.[31-33] During platform perturbation, Marigold et al.[34] found significant differences in tibial anterior response under different weight bearing loads in controls but not in the subjects poststroke. This implies a difference in the preparatory response even in induced stepping in stroke survivors compared to controls.

Joint kinematics and ground reaction forces at landing as well as other step characteristics such as width or length may also be different during induced stepping in persons poststroke. During voluntary stepping, foot contact tends to be more lateral and with a flat foot in persons poststroke,[32,35] therefore landing of the first step after a perturbation may impact stability in stroke survivors. Relationships between clinical measures such as range of motion and strength may assist in identifying the underlying factors that may impact the protective stepping response.

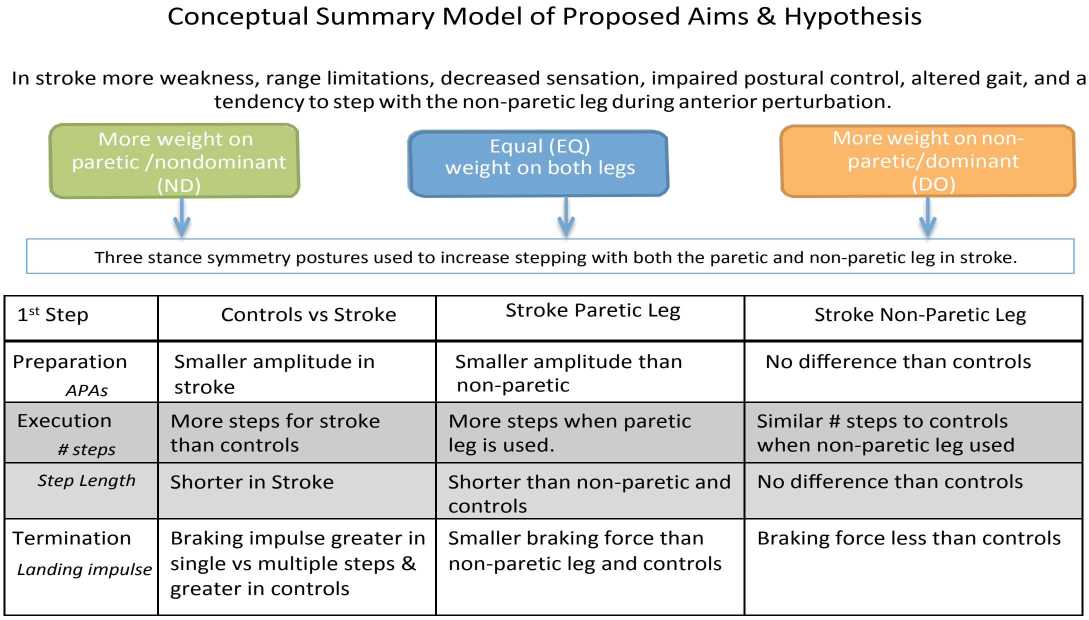
Characterizing the different phases of perturbation-induced stepping (preparation, execution, landing) in stroke survivors could provide important information for design and implementation of dynamic balance interventions.

Purpose of the Study

The purpose of this study was to investigate the similarities and differences in perturbation-induced protective stepping between ambulatory community-dwelling stroke survivors and age and gender-matched controls at three phases of the stepping response (preparation, execution, and landing) in three different stance symmetry positions. The secondary purpose was to investigate potential correlations between stroke-related deficits and induced protective stepping and also to identify between limb differences in perturbation-induced stepping.

Research Question and Hypothesis

A conceptual summary model underlying the aims and hypothesis is presented in figure 1.



Conceptual Summary Model of Proposed Aims & Hypothesis

In stroke more weakness, range limitations, decreased sensation, impaired postural control, altered gait, and a tendency to step with the non-paretic leg during anterior perturbation.

Three stance symmetry postures used to increase stepping with both the paretic and non-paretic leg in stroke.

1st Step	Controls vs Stroke	Stroke Paretic Leg	Stroke Non-Paretic Leg
Preparation *APAs*	Smaller amplitude in stroke	Smaller amplitude than non-paretic	No difference than controls
Execution *# steps*	More steps for stroke than controls	More steps when paretic leg is used.	Similar # steps to controls when non-paretic leg used
Step Length	Shorter in Stroke	Shorter than non-paretic and controls	No difference than controls
Termination *Landing impulse*	Braking impulse greater in single vs multiple steps & greater in controls	Smaller braking force than non-paretic leg and controls	Braking force less than controls

Figure 1: Conceptual summary model of proposed aims and hypothesis. ND = nondominant, EQ = equal, DO = dominant, APA = anticipatory postural adjustment, NP = non-paretic.

Aim 1: to identify differences in the kinetic and kinematic measurements of perturbation-induced protective steps in chronic stroke survivors and age- and gender-matched controls.

- H1a: There will be a significant difference in the preparation phase of the first perturbation-induced steps as measured by the ground reaction forces prior to foot lift off between groups for each stance symmetry position.
- H1b: There will be a significant difference in the execution phase of the perturbation-induced protective step characteristics (step height, length, width, duration, number of steps) between stroke subjects and age- and gender-matched controls for each stance symmetry position.
- H1c: There will be a significant difference in the landing phase as measured by the ground reaction forces and speed at landing of the first step between groups for each stance symmetry position.

Aim 2: to identify differences between legs in kinetic and kinematic measurement of perturbation-induced protective stepping in chronic stroke survivors.

- H2a: There will be significant difference between paretic and non-paretic leg in the APA (anticipatory postural adjustment) peak, step length, height and number of steps, and ground reaction force at landing.

Aim 3: to identify any potential associations between specific stroke-related clinical outcome measures and selected perturbation-induced step variables

- H3a: There will be a moderate statistically significant correlation with lower extremity motor control and force at landing.
- H3b: There will be a significant correlation between Step Test score and step duration.

- H3c: There will be a negative correlation between the balance confidence score and the mean number of steps.

Definitions of Terms

Anticipatory postural adjustments (APA) – changes in muscle activation, weight shifts, and ground reactions forces that occur prior to movement in an effort to counteract the disruption to the system and maintain postural stability.

Center of Mass (COM) – center point of the total body mass.

Center of Pressure (COP) – weighted average of all ground reaction forces of the surface in contact with the ground.

Dynamic standing balance – ability to effectively regulate the relationship between body center of mass (COM) and the base of support (the feet). Can include proactive and reactive balance control.

Fall – inability to maintain upright control of the body resulting in person coming to rest unintentionally on a lower surface.[8]

Ground reaction forces (GRF) – the horizontal and vertical forces exerted by the ground on the body in contact with it. The GRF is equal in magnitude and opposite in direction to the force the body is exerting on the surface it is in contact with.

Landing phase of stepping – refers to the ground reaction forces and ankle angle at foot contact of the first step.

Perturbation – an external force acting to disrupt the ability to maintain upright posture.

Perturbation-induced protective steps – balance responses that occur as a result of an external perturbation.

Preparation phase of stepping – refers to the APA (anticipatory postural adjustment) prior to step onset.

Proactive balance – postural control of the body when movements are self-initiated.

Protective steps – steps that occur in an attempt to regain one's balance. This can be initiated voluntarily in response to anticipation of a fall or reactively to an unexpected perturbation.

Reactive balance – any response to an external perturbation expected or unexpected. Can include feet-in-place or change of support strategies.

Static balance – ability to control the body center of mass over a stationary base of support without having to alter the base of support.

Execution phase of stepping - kinematic step characteristics such as step onset, height, length, width, duration, or number of steps.

Summary

The ability to rapidly move the feet to catch one's balance has been highlighted as a common strategy in everyday situations, yet little is known about the protective stepping characteristics in persons poststroke. Sixty percent of stroke survivors are ambulatory and have neuromuscular-somatosensory impairments that may impact their protective stepping strategy. The first chapter introduced the strategy of protective stepping in persons poststroke and the relationship between balance and falls. The purpose of the study, relevance, research questions, and hypothesis for the study were presented.

Chapter 2: Review of the Literature

Introduction to the Chapter

Chapter 2 begins with an overview of the incidence and prevalence of stroke and risk factors for falls in people poststroke. A review of postural control in non-impaired persons and persons poststroke are discussed, and terminology used to describe postural responses to different challenges are presented. A review of the literature on perturbation-induced protective stepping in persons poststroke and a summary of clinical measure for assessing standing balance in poststroke survivors is also discussed.

Epidemiology of Stroke: Incidence, Prevalence, and Characteristics

Stroke affects 795,000 people annually in the United States, and although there has been a decrease in the age-adjusted annual incidence of stroke over the last 50 years, the severity of stroke has not diminished.[36,37] Stroke is a major cause of disability and the fifth-leading cause of death in the United States with a higher prevalence in older adults, some minorities, and persons with lower educational levels.[38] Direct medical cost for strokes are projected to increase 238% by 2030 with indirect cost of lost productivity to reach $42 billion.[39]

Stroke can be classified into four major pathological categories: ischemic (large-artery disease, cardioembolitic, small artery disease, others), intracerebral hemorrhage, subarachnoid hemorrhage stroke, and undetermined.[40] Ischemic strokes are the largest group ranging from 67 to 81% of all strokes.[40] Disability from stroke is common with 44% having moderate to severe deficits six months post.[41] Stroke can occur in any age; however, the risk of stroke increases with age, and 72% of strokes occur after age 65.[36,41] Disability poststroke is significantly greater than age- and gender-matched controls.[41]

Impairments poststroke include sensory, motor, and visual impairments; pain; alterations in muscle tone; and development of synergy patterns which lead to functional deficits in speech, cognition, swallowing, balance, mobility, and various disabilities. A major component of stroke rehabilitation is gait and balance training, yet as many as 20% of all stroke survivors remain wheelchair bound three months after a stroke, and another 60% are limited in their walking.[13]

Falls and Risk Factors for Falls Poststroke

Falls in persons poststroke occur more frequently than falls in older adults.[1] Individuals who fell in the hospital after a stroke are twice as likely to fall at home.[42] Compared to the general population, there is a seven-fold increase in fracture risk within the first year of a stroke that declines over time but does not reach baseline levels for age-matched peers.[42]

Unlike falls in the hospital which occur most often during transfers, falls in community-dwelling poststroke survivors occur frequently (39-90%) during standing and walking.[2] Studies on stroke survivors have identified numerous risk factors for falls such as motor and sensory deficits, mental decline, incontinence, gait deficits, poor balance, and a fear of falling.[3-5] However, clinical measures of balance, gait, and cognition were not found to be associated with falls,[6] illustrating the complex relationship between balance and fall risk in the stroke population.

One might think that falls are more common in stroke survivors who present with more severe impairments and limitations in balance and mobility; however, research has not supported this hypothesis. Studies looking at community-dwelling chronic stroke survivors found no difference in impairments or function between those who had fallen (fallers) and those who had not fallen (less-fallers).[3,7,8] Belgen et al.[7] looked at the six-month fall history of 50 stroke survivors and classified them as fallers or non-fallers. The participants had a wide range of stroke onset time (3-312 months post), and were able to walk at least 10 meters independently with or without an assistive device. No difference was found in the five time Sit to Stand test, score on the Lower Extremity Fugl Meyer Assessment, or the Timed Up and Go test between those individuals who reported a fall versus those who reported no falls. In contrast, severity of stroke as measured by the number of impairments was linked to lower fall risk in a study by Yates et al.[3] They suggest that the higher number of impairments (motor, sensory, and visual deficits) resulted in decreased mobility, thereby lowering the subject's risk for falls due to increase need for assistance during movement and mobility.

Hyndman et al.[8] found no significant difference in measures of mobility, activities of daily living (ADL), arm function, and depression between 41 community-dwelling stroke survivors (3-288 months post) who were identified as fallers and less-fallers. The majority of the falls occurred toward the affected side (62.8%), and in 50% of the near-falls subjects stated that they used arm movement to recover their balance, often to grab onto something, with 56% of those stating they used both arms. A post hoc analysis revealed repeat fallers had significantly reduced arm function and ADL abilities compared to those who had no falls.[8] The authors felt this relationship may be indicative of the stroke severity or possibly the diminished capacity of the arm to assist in preventing a fall. They concluded that fallers poststroke are not a homogeneous group and that a more complete picture is needed to identify risk factors for falls in community-dwelling stroke survivors.

Based on the aforementioned data on falls poststroke, one might assume that individuals with greater mobility might be at greater risk for falls. However, a study by Harris et al.[6] found no significant difference in self-selected (0.60m/s vs. 0.67m/s) or fast-pace gait speed (0.84m/s vs. 0.91m/s) and balance as measured with the Berg Balance Scale (43.4 vs. 44.9) between chronic stroke survivors who had fallen and those who had not fallen. The majority of falls in these investigations occurred during walking and standing activities that require dynamic and reactive balance control.

Postural Control in Standing

Postural control involves both the ability to orientate the body against gravity and control the body segment over their base of support to serve as a reference point for movement and interaction with the external world.[43,44(p158-159)] Balance, sometimes also called postural stability, is the ability to control the center of mass (COM) in relation to the base of support so as to prevent the body from falling.[45(p161-182)] The total body COM is calculated from the weighted average of the COM of each body segment and is the center point of the body. Controlling the COM effectively and efficiently over the base of support requires coordinated interaction of the neuromuscular system.[44(p161-182)]

During weight shifts and stepping, the COM moves and the body must make adjustments to compensate for the disruption of the COM movement in order to maintain upright control. Anticipatory postural adjustments (APA) lead and accompany these movements to minimize postural disturbance and allow for a stable frame from which the body segments may move. Anticipatory postural adjustments typically move in the opposite direction of the task and involve activation of muscles and changes in ground reaction forces. A point called the center of pressure (COP) represents the sum of all the ground reaction forces (vertical, medial-lateral, and anterior-posterior). In single leg stance, the COP is within the boundaries of the foot. In bipedal stance the net COP is somewhere between the two feet depending on the distribution of the weight between the two feet.[45] During initiation of voluntary forward stepping the COP moves posterior and towards the stepping limb as the COM moves forward and toward the stance leg.[45]

At unloading, the COP moves forward and under the stance limb as the COM accelerates forward away from the stance leg. This movement of the COP is often used to quantify the APA.

Alterations in APAs have been identified during step initiation in Parkinson's Disease (PD)[46] and stroke[30] gait pathologies. In PD, self-initiated steps are associated with increase durations and decrease magnitude of the COP shift.[46] In stroke subjects there was significant differences ($p < .007$) in the mean relative COM velocity from the onset of the step to toe off between initiating stepping with the involved (17.2%) and the less-involved leg (50.5%).[30] The initial movement of the COM toward the stance leg (less affected) when the first step was taken with the affected leg was in the same direction as controls. However, when stepping with the less-affected leg there was no transient movement of the COM to the stance leg before toe off.[30] Regardless of which leg is used, stroke survivors took almost twice as long to initiate gait compared to controls.[31]

Balance Response to External Perturbation

Balance responses to external perturbation have been classified into two categories, fixed base of support and change in support responses. Fixed base of support responses include any balance response in which the base of support does not move. This includes arm or trunk movements as well as the commonly known ankle and hip strategies.[47,48] Ankle strategies are typically used in situations in which the perturbation is small and the individual has adequate ankle strength and range of motion to counteract the external forces. It has been suggested that the hip strategy is used when the support surface is small or compliant and in response to larger, faster perturbations. These strategies, however, are not discrete and operate on a continuum in conjunction with each other and whole body movements.[22,44(p212-231)]

Change in support strategies are used to increase the base of support and may include reactive stepping, as well reaching or grasping an object to maintain upright posture.[49,50] These responses were historically thought to be a strategy of last resort, used when all other balance responses were ineffective. More recent literature has shown that reactive stepping often occurs before the limits of stability are reached, and older adult fallers step earlier compared to non-fallers and younger adults.[23,51,52] These induced steps are thought to be a preselected decision to step.[23]

Induced steps are executed faster than voluntary steps and can be as fast as the young in older adults.[23] In older adults, strength, lateral foot placement, and multiple protective steps have been linked to falls.[53,54] When compared to voluntary stepping, perturbation-induced APAs are less frequent (56% vs. 100%), smaller (0.2cm vs. 1.5cm[29]), and, for older adults, shorter in duration (0.18s vs. 0.26s, $p = 0.027$) than for young adults.[23] Surface electromyography recording of postural reflex during posterior platform perturbations showed differences ($p<0.05$) in the onset of medial gastrocnemius with different weight-bearing conditions for controls (more weight 102.5ms; less weight 115.4ms) but no significant difference in stroke subject with either paretic (more 136.8ms vs. 141.1 less) or non-paretic (more 118.9ms vs. less 115.9ms).[34] This indicates a difference in postural preparation and execution strategies for different types of step and gait pathologies compared to non-impaired controls.

Postural Control Response Poststroke

Impaired standing balance is often observed in persons poststroke and is characterized by increased weight bearing on the stronger, less-involved lower extremity and increased postural sway.[55,56] This increased postural sway has been correlated with reduced synchronization between limbs.[57] Shifting weight is also impaired in persons poststroke. Stroke survivors demonstrated significant difference in their ability to weight shift onto the involved and less-involved limb when placing one foot up on a step or during transition from bipedal to single limb stance.[58,59]

In standing, self-initiated perturbations produced by rapid arm elevation showed delayed and reduced lower extremity muscle activation on the involved side with increased activation of less-involved leg muscles in individuals poststroke compared to healthy age-matched controls.[15,60,61] When given sudden external lateral perturbation at the pelvis in standing, individuals poststroke display impaired balance responses compared to healthy controls, with delayed onset and decrease gluteus medius and adductor activation on the paretic side, while the non-paretic adductors muscle activation was higher and had a similar onset as controls.[16,62] This illustrates the impairments of muscle activation in the lower extremity muscles and slower reactions times for standing upright tasks in persons poststroke. Kirker et al.[16] however found a more normal activation of the hemiparetic muscles during stepping as compared to standing perturbations, suggesting that these two tasks are neurophysiologically distinct.

Significant differences have also been reported in the kinetic and kinematic data during transition from bipedal stance to gait initiation between involved and less-involved legs in persons poststroke as well as between controls and stroke survivors.[30-33] Anticipatory postural adjustments were significantly ($p<0.05$) longer in duration, when stepping with the less-involved (0.77 sec) compared to the involved leg (0.58 sec), and the swing time of the involved leg was longer than the less-involved leg (0.52 and 0.35 sec respectively, $p<0.05$).[32] Increased medio-lateral sway of the COP was noted when initiating gait with the less-involved leg (17.4cm) compared to the involved leg (10.4cm) but not different than controls (13.7cm).[30] Even when controlling for differences in speed of stepping between controls and stroke survivors, the anterior-posterior impulse to initiate stepping was less when leading with the paretic (0.00Ns/kg) compared to non-paretic leg (0.13Ns/kg) and controls (0.07Ns/kg).[31]

Induced Balance Recovery Stepping Poststroke

Limited information about perturbation-induced stepping for balance recovery after stroke indicates that steps are initiated primarily with the less-involved limb in both acute and chronic stroke.[19,21,34] Falls during inpatient rehabilitation have also been related to lack of foot clearance during induced stepping.[20] One retrospective chart review concluded that increased lower-limb motor recovery scores and weight bearing on the less-involved limb were related to increased frequency of stepping with the involved limb in acute stroke survivors.[27] However, another study found diagonal perturbations towards the less-involved side, increased the frequency of stepping with the involved leg from 33% to 51.7% compared to straight forward perturbations.[21] This suggests that the initial weight-bearing asymmetry could impact which leg moves in the release of recovery step.

While these studies provide beginning information on induced stepping in stroke survivors, only two studies were found that compared stepping responses to external perturbations in stroke survivors and controls.[34,63] These studies were not designed to investigate the stepping response in the stroke survivors, but both studies reported that stroke subjects fell more often than controls, indicating that the stepping responses for the stroke participants were less effective. Given that individuals poststroke tend to stand asymmetrically, additional information on the effects of weight bearing on postural preparation, execution, and landing of perturbation-induced stepping response was important in guiding the design and implementation of both balance treatment interventions and assessments.

Clinical Assessment of Standing Balance

There are numerous clinical standing balance outcome measures that are used with the stroke population.[64,65] Many of these measures focus on static and dynamic control with few of them directly assessing reactive response. The most commonly used clinical balance measure is the Berg Balance Scale.[66] This tool includes 14 static and dynamic tasks starting with moving from sitting to standing to standing on one leg with a maximum total score of 56 points and a cut-off score of 45 for stroke survivors.[67] Other standing balance assessments include Step Test,[12,68] Time Up and Go (TUG),[69] Functional Reach,[70] Dynamic Gait Index,[71] and the Mini-BESTest©.[72] Assessments of standing balance are also embedded into multidimensional outcome measures such as the Postural Assessment Scale for Stroke Patients (PASS),[73,74] the Fugl-Meyer Assessment of Sensorimotor Recovery after stroke (FMA),[75,76] and the Tinetti Performance Oriented Mobility Assessment (POMA).[77,78] Patient-reported outcome measures of balance confidence and fear of falling such as the Activities-specific Balance Confidence scale[79-81] or the Tinetti Falls Efficacy Scale[82,83] are also utilized. Each of these measures is different in cost, time, training, equipment, psychometric properties and domains of balance dysfunction they address.

Only two of the aforementioned outcome measures, the Mini-BESTest© and the POMA, include a reactive component to an external perturbation in their balance assessment, and both utilize an ordinal rating scale. A new reactive balance assessment was recently developed for use with community-living older adults. The Spring Scale test[84] utilized a percentage of body weight through a linear spring secured around the persons' waist. The spring is pulled and then released to create a perturbation. The maximum force that the subject could tolerate without stepping or falling was recorded as a percentage of the persons' total body weight (TBW%). The authors found a significant difference in the mean TBW% between fallers and non-fallers in 58 older adults and the area under the curve (AUC) was higher than the TUG.[84] These measures provide an option for assessing postural responses to perturbations, but the relationship to other clinical measures is not known.

Perturbation Methods

External perturbations to standing balance in persons poststroke has been facilitated through various devices such as lean and release method,[85] pelvic push,[16] the EquiTest system,[62] moving platform,[86] cable pull,[21] and the weight dropping system.[63] The moving platform and EquiTest system require specialized equipment that is expensive and not available at our facility. The lean and release method requires the subject to actively lean forward from the ankle with 5-10% of their body weight supported by a cable at the thoracic level which is then released at an unexpected time. Many persons poststroke have difficulty not only controlling their body movement in specific directions but also maintaining altered postural positions. A cable pull weight dropping system using a percentage of the subjects' body weight has been used as a perturbation to pull the subject off balance in individuals poststroke as well as young and older adults.[26,63,87,88] Response to the weight dropping system in individuals poststroke has been reported in the posterior direction, and similar systems have been used with older adult fallers in multiple directions.[24,26,63,88]

Pilot Study

A pilot study was completed prior to this project to determine the anterior perturbation intensity needed to produce a stepping response in persons poststroke and controls. A weight drop system has been fabricated using a rigid belt, wire cable, electromagnet, and metal weights on a vertical pole that dropped 52 cm (figure 2). Fourteen poststroke survivors and nine age- and gender-matched control subjects participated in the pilot study.

The mechanical weight drop waist pull perturbation was applied at random intervals (1-3.5 seconds) in the anterior direction using 2%, 5%, 8%, and 10% of the subject's body weight (BW). Six trials at each perturbation intensity, and six catch trials (no perturbation) were applied in a standard randomized order. Subjects poststroke were able to complete all 30 trials without rest breaks. A statistically significant difference was found in the mean number of steps between subjects poststroke and control subjects at 10% BW, and both groups always stepped at this intensity (Appendix A). Based on these results, the mechanical weight drop system and 10% BW were used in this study as the perturbation method.

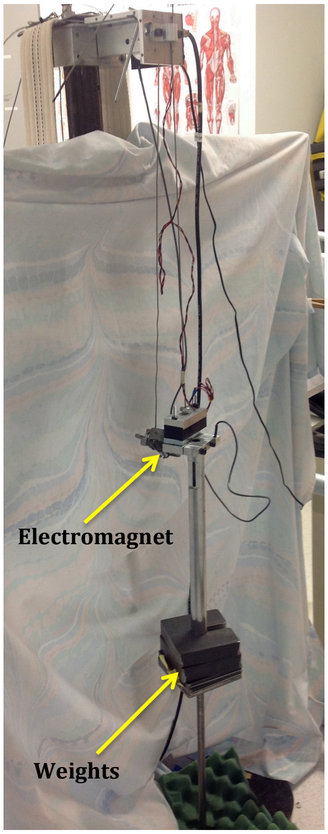


Figure 2: Weight drop system

Contributions to the Profession

This study responds to the gaps in the literature regarding the impact of stance symmetry protective stepping and provides important information regarding perturbation-induced protective stepping response in stroke survivors and age-matched controls. The information about the different phases (postural preparation, execution, and landing) of perturbation-induced protective stepping can assist clinicians and researchers in designing interventions that address the appropriate phase of this dynamic postural response as it applies to the stroke population.

Chapter 3: Methodology

Introduction to the Chapter

This study was a non-randomized, age and gender-matched, controlled study. This chapter describes the research method, specific procedure for the study, and statistical plan including sample size and method of data analysis. Availability of laboratory equipment and resources are addressed as well as rationale and justification of clinical measures.

Research Methods

Subject Recruitment

Subjects post-stroke were recruited from the Clinical Neuroscience Research Registry, a database stroke survivors developed by collaborating researchers at the Rehabilitation Institute of Chicago. Control subjects were recruited from the Northwestern University Buehler Center Aging Research Registry and from flyers posted on campus. Potential subjects were contacted by phone calls to assess their interest and eligibility for the study (see Appendix B).

Inclusion and Exclusion Criteria

All subjects were screened by phone to verify the inclusion criteria. Subjects poststroke met all of the following criteria: 1) primary diagnosis of a single unilateral non-cerebellar stroke at least one year prior to their participation in this study; 2) lived independently in the community; 3) able to follow three-step commands and give informed consent; 4) 21 years of age or older; 5) not currently receiving occupational or physical therapy; 6) able to stand and walk 10 feet without an assistive device or orthosis; 7) able to negotiate stairs and ramps independently with or without an assistive device and/or ankle foot orthosis; and 8) able to ambulate independently in the community without using a wheelchair.

Control subjects were gender and age-matched (±3 years), community-dwelling volunteers who were 1) medically stable, 2) without neurological impairments, 3) ambulating without an assistive device, and 4) functioning independently, without significant deficits in hearing, vision, or mental capacity that would interfere with the testing procedure.

Subjects were excluded if they had orthopedic injuries that may alter movement such as fractures, surgeries, and pain or endurance issues that limit walking or ability to perform activities of daily living, or were currently receiving physical or occupational therapy. They were also excluded if they had other neurological disorders (e.g., Parkinson's Disease, Multiple Sclerosis, Ataxia, Vestibular Dysfunction) or had any orthopedic issues (e.g., joint replacement, fusions) that may alter movement patterns, or have any other medical condition that limits their ability or their functional mobility. Subjects over 300 lbs. (138 Kg) were excluded based on limitations related to the maximum weight capacity of the perturbation device.

Sample Size

A post hoc power analysis of step onset data from a pilot study on 14 stroke and nine control subjects at 10% BW perturbation (difference in mean = 0.382, SD = 0.246 for stroke and 0.189 for controls) showed a total of 16 stroke and 12 control subjects would be needed for power of 0.8 and significance of 0.05. A previous study on step initiation with controls and stroke found a significant difference between stepping limbs in stroke subjects for step duration and APA as measured by the COP utilizing 10 controls and 14 stroke subjects.[30] They also showed that initiating stepping with the involved leg was more similar to steps taken by the control subjects than steps taken with the less-involved leg. Significant differences ($p<0.01$) were found in speed of gait initiation and anterior-posterior impulse when leading with the paretic limb between 13 individuals with chronic stroke and 13 healthy controls even when controlling for speed of gait.[31] For all these reasons, a sample size of 40 (20 stroke and 20 controls) was thought to be realistic and large enough to show significant difference between stroke and age- and gender-matched controls in the APA, step characteristics, and kinematic and kinetics at landing of the first step.

Informed Consent

Institutional review board (IRB) approval for this study was received from both Northwestern University (NU) and Nova Southeastern University (NSU) for 45 subjects to account for withdraws or lost data. Information about the rationale for the study and the potential risk and benefits were discussed with each subject during the initial contact. All subjects who participated in this study reviewed and signed approved consent forms from both universities and received copies of each.

Experimental Protocol

First, subject's height and weight were measured with their shoes on. Date of birth, gender, month and year of stroke onset, involved side, and type and location of stroke were also recorded. The clinical tests and induced protective stepping are described below and were administered in one session in the following order: Step Test (ST), measurements of ankle range of motion, sensation of foot, lower extremity motor control test (UMCe), Timed Up and Go test (TUG), the Activities-specific Balance Confidence scale (ABC) with the induced protective stepping trials always performed last.

Clinical Tests

The clinical tests were selected to give a fuller picture of the subjects based on the various domains of the International Classification of Functioning, Disability, and Health (ICF):

ankle range of motion (ROM), Upright Motor Control extension test (UMCe), and sensation of the feet to represent the body structure function domain; the ST and the TUG to assess balance and mobility representing the activity domain; and the ABC to assess participant balance confidence as a measure of personal factor.

The Step Test (ST) was designed to assess dynamic balance in persons poststroke and has been used with community-dwelling stroke survivors.[12,68] The individuals were asked to stand and place their whole foot up on a step 7.5 centimeters high as many times as they could in 15 seconds first with their affected leg and then with their unaffected leg.[12] The score for each leg was the number of times a subject touches the step in 15 seconds. Test-retest reliability Intra-class Correlation Coefficients (ICC) is high for stroke patients ranging from 0.88-0.97, with Coefficients of Variation ranging from 0.10-0.20.[68]

Goniometric measurements are commonly used to assess range of motion in the clinic. Norkin and White[89] report large variability in interrater reliability (ICC .28 to .97) depending on the population, but high intratester reliability (ICC .74 to .98), with ICC of .90 in one study with patients with orthopedic and neurological problems.[90]

Deep pressure sensation in the foot were measured using Semmes-Weinstein aesthesiometer.[91] This method has been found to be reliable in the diabetic population and has been used with stroke subjects in research studies.[56,92,93] This measure is also on the list of recommended outcome measures by the StrokeEDGE group[94] of the Neurologic section of the American Physical Therapy Association, but no studies on the measures of psychometric parameters in stroke subjects could be found.

Testing strength in persons poststroke is complicated due to the presence of synergy patterns, altered motor recruitment patterns, and spasticity in some patients. Although isokinetic strength testing machines have been used successfully in past studies, access to this type of machine was not available. One way to assess functional voluntary muscle strength in the hemiplegic leg is with the Upright Motor Control extension test (UMCe).[44,95,96(p404)] In this test the individual poststroke bends both knees approximately 30° with light upper extremity support for balance and then lifts the less-involved leg off the ground. In this single leg support position the ability of the involved knee to extend is graded strong if able to fully extend, moderate if able to support on flexed knee, and weak if unable to support on flexed knee. The closed chain position is similar to the leg extension position needed for the landing phase of the induced step. Although no published studies could be found on the reliability or validity of this test, knee extension strength has been shown to be related to gait speed, functional ambulation, and Berg Balance Scale.[97,98]

The Timed Up and Go test (TUG) is an outcome measure that has been used with persons poststroke to assess fall risk, balance, and mobility.[69] To complete this test, subjects began seated with their back against the chair. On “go,” the subjects rise from the chair, walk three meters at their normal pace, turn around, walk back, and sit down. This test has been shown to have strong test-retest reliability (ICC of 0.96) in chronic stroke subjects and a strong significant correlation ($p < 0.001$) to fast walking speed ($r = -0.91$) and 6 minute walk test ($r = -0.92$).[69] The average TUG score in individuals poststroke is reported to be 22.6±8.6 seconds, while the average for healthy older adults was 9.1±1.6 seconds.[99]

The Activities-specific Balance Confidence (ABC) scale is a questionnaire that asks the participant how confident they are in performing 16 functional activities using a rating of 0% (no confidence at all) to 100% (complete confidence).[79] Scores above 80 indicated high balance confidence and decreased likelihood of falls. The ABC has been shown to have good internal consistency (.94) and test-retest reliability (ICC = 0.85) among individuals poststroke.[80] It has fair to moderate correlation to gait speed (*p* =.49), Berg Balance Scale (*p* =.44), and SF-36 Physical Function scale (*p* =.59).[81]

Induced Protective Stepping

Reflective markers were placed bilaterally on the medial and lateral malleolus, medial and lateral femoral condyles, lateral mid tibia, calcaneus, lateral first and fifth metatarsal head, and top of second metatarsal head to record the stepping response. Subjects were placed in a safety harness attached by straps to an overhead rigid beam that allows subjects to move freely and minimizes falls. A rigid belt linked to a cable attached to the mechanical weight drop device was secured to the subject's waist, and the cable height was adjusted to the level of the umbilicus (figure 3).

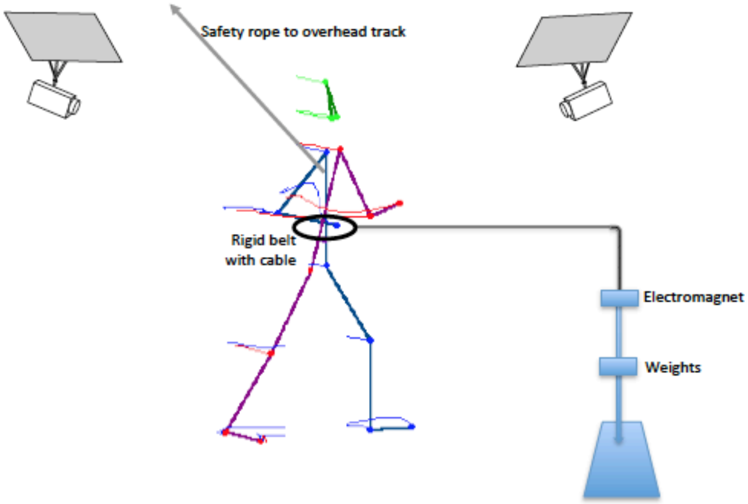


Figure 3: Diagram of induced stepping laboratory method with weight drop device, cable, and safety rope attached to subject.

Subjects were instructed to stand with feet shoulder-width apart, each foot on a separate force plate. The placement of the feet was traced to allow the subject to return to the same foot position for each trial. A mechanical weight drop system delivered an anterior perturbation equal to 10% of the individual's fully clothed body weight (10% BW). This pull was triggered when the subject maintained a pre-instructed weight-bearing load on the force plate for 250-1000ms. The perturbation device was behind a screen, and a monitor provided visual feedback to the subjects on their standing weight-bearing symmetry. Three different stance symmetry postures were used to facilitate stepping with the paretic leg in stroke. The stance symmetries were: equal weight between the legs (EQ: 50% ±3), more weight on the dominant leg (DO: 70% ±3), and more weight on the nondominant leg (ND: 70% ±3). These values are based on the abilities of subjects poststroke to shift weight onto their involved leg in prior studies and in pilot testing.[34,100] The dominant leg was assumed to be the non-paretic leg for stroke subjects as seen clinically.[55,56,101] The dominant limb for controls was determined by the leg they choose to perform single limb stance.[102-104]

All subjects were given three practice trials of increasing weight bearing to the predetermined level onto each leg using the monitor for visual feedback. They were instructed to react naturally and not resist the waist pull perturbation. Thirty-five trials, 10 at each of the three stance symmetry postures and five catch trials at 2% BW were presented in a predetermined standard randomized order (Appendix C). Subjects were given a seated rest after 18 trials or as needed. A research personnel was standing next to the subject at all times for safety.

Laboratory Measures and Setup

Ground Reaction Forces: The ground reaction forces were measured with four six-channel strain-gauge force platforms (Model OR6-5-1000 and OR6-7-1000, AMTI, Newton, MA) imbedded into a raised laboratory floor in a square configuration. The vertical ground reactions forces from the two force plates the subject was standing on were displayed on a monitor for the weight-bearing strategies. Data was collected at 100Hz for 15 seconds beginning at least one second before the perturbation.[105]

Kinematic Recordings: An eight-camera motion analysis system (QTM-Qualisys Tracking Manager, Qualisys, Gothenburg, Sweden) was used to capture bilateral reflective markers at 100 Hz. Markers were attached bilaterally over key landmarks to record foot and shank movements, to record number of steps, step height, length, width, and ankle angle. Perturbation, kinetic, and kinematic data was collected and synchronized in Qualisys. Data was filtered using a second order Butterworth filter with 1 bidirectional pass resulting in a fourth order filer. The cutoff frequency was set at 10Hz.[28,106]

Chapter 4: Results

Introduction to the Chapter

This chapter will describe the data analysis and findings of this study. Difference between the stroke and control groups for the preparation phase (anticipatory postural adjustments or APA), execution phase (step characteristics), and landing phase (landing speed and impulse) for each of the stance symmetry stepping responses will be identified. Correlation findings between selected induced step variables and clinical tests are presented. Descriptive statistics on subject characteristics and results of the comparison between legs within each group are also presented in this section.

Participants

Forty-two participants were consented for this study, 25 stroke survivors and 17 controls. Four stroke individuals were not included in the analysis, as they did not complete testing because of unsafe stepping without their orthosis during the induced stepping task. Twenty-one stroke survivors, 15 men and 6 women (mean age 55.9±13.3 yrs., chronicity 9.3±6.6 yrs.)—and 17 control subjects—10 men and 7 women (mean age 54.4±17.4 yrs.)—were used in the analysis. All subjects poststroke had unilateral weakness (six right-side weakness), lived and ambulated independently in the community with or without assistive devices, were able to walk indoors at least 50 ft. without brace or cane, and gave informed consent. One subject poststroke completed only 21 out of the 36 trials due to fatigue. There was no significant difference in age (U=177.5, Z=-.029, p=.977), height (U=54, Z=-.720, p=.471), or gender (U=156, Z=-.804, p=.422) between the two groups. The stroke group walked slower, had decreased balance confidence, less dorsiflexion range of motion and less extension control on the paretic leg than the controls (table 1).

Subject Clinical Data	Control n=17		Stroke n=21	
	Mean	SD (range)	Mean	SD (range)
Age (yrs)	54.47	17.39 (22-82)	55.90	13.28 (21-80)
ABC (0-100%)*	*92.96*	10.72 (57-100)	*80.96*	11.26 (55-95)
TUG (sec)*	*8.52*	1.51 (6.1-11.4)	*14.41*	5.43 (8.53-31.26)
Step Test - nonDom*	16.59	3.32 (13-23)	8.24	2.98 (4-16)
Step Test - Dom*^	17.65	3.06 (14-22)	9.90	3.30 (4-14)^
DF range - nonDom*	7.12	3.77 (-2-12)	-2.00	6.48 (-18-13)
DF range - Dom^	7.88	3.97 (-4-14)	7.52	5.94 (-2-19)^
Sensation - nonDom(g)	1.65	1.19 (.4-4)	3.30	3.00 (.4-10)
Sensation - Dom (g)	1.53	1.03 (.4-4)	2.04	2.12 (.4-10)
UMCe - nonDom*	*1.00*	.00	*1.55*	.686 (1-3)
UMCe - Dom	1.00	.00	1.40	.754 (1-3)

Table 1: **Subjects' clinical data. ABC (Activity-specific Balance Confidence Scale), TUG (Timed Up and Go test), nonDom (nondominant leg), Dom (dominant leg), DF (dorsiflexion), UMCe (Upright Motor Control extension test). * indicated significant difference between groups, ^ indicated significant difference between paretic and non-paretic legs in stroke ($p<0.05$).**

Data Analysis

Ground reaction forces and kinematic recording for the induced protective steps were analyzed during the three phases of the stepping response (preparation, execution, landing) using customized interactive graphic analysis MatLab programs. Techniques used to process the data in each phase are described below.

Preparation Phase

The preparation phase is defined as the period of time from the onset of the pull to the foot lift off. It is the phase where the body is adjusting the COM in preparation to move from bipedal stance to stepping. An APA was identified if there was an increase in the initial step side vertical force and simultaneous decrease in the stance side force with an initial shift in the net mediolateral COP toward the first stepping limb. The preparation phase characteristics were derived from the net mediolateral COP displacement, referred to as APA, characterized by an initial displacement of the COP toward the stepping leg (figure 4). The onset was defined as the beginning of the COP displacement, that is, when the first derivative becomes continuously greater than zero. The APA amplitude or peak was the maximum displacement of the net COP toward the stepping side, and the APA duration was from the onset of the COP displacement to the APA Peak.

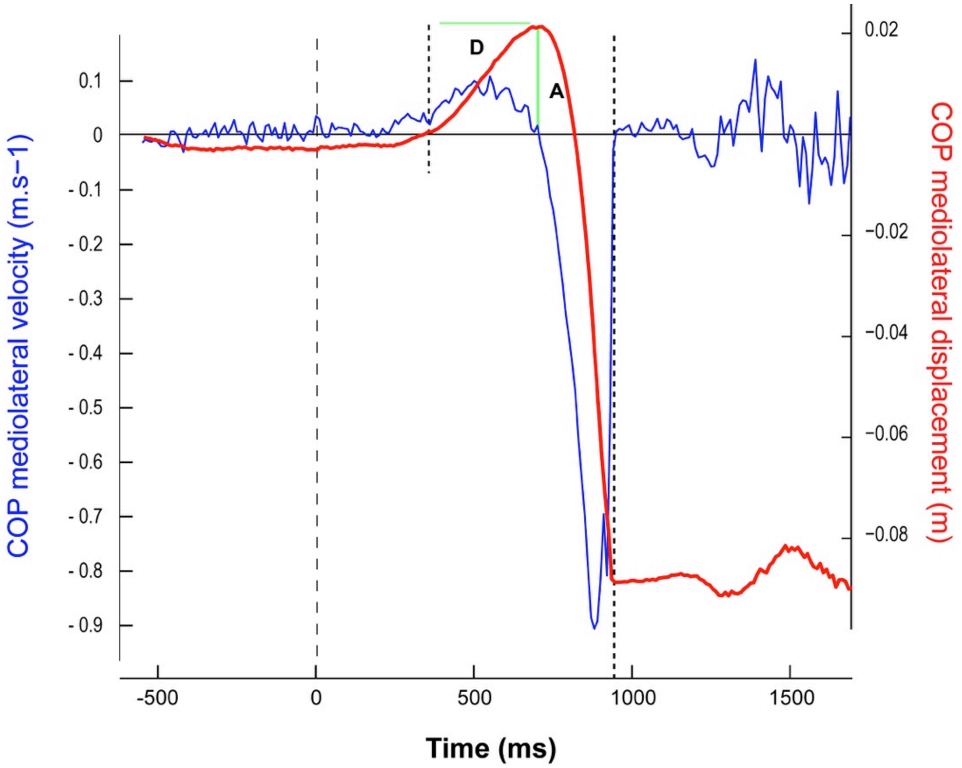


Figure 4: Determination of APA. Representative example of mediolateral displacement of the COP from which the duration (D) and the amplitude (A) of the APA were determined. Time zero is onset of the perturbation.

Execution Phase

The execution phase corresponds to initial stepping characteristics. For each trial, the number of steps, step onset, length, width, height, and duration were determined. The first step characteristics were identified from the ankle markers of the stepping side. The beginning and end of the first step were identified from the vertical velocity of the step side ankle marker in order to determine the step duration and the mediolateral and anteroposterior displacement for step width and length (figure 5). The step clearance was defined as the maximal vertical excursion of the step ankle marker. The onset time of stepping was calculated relative to the onset of the perturbation.

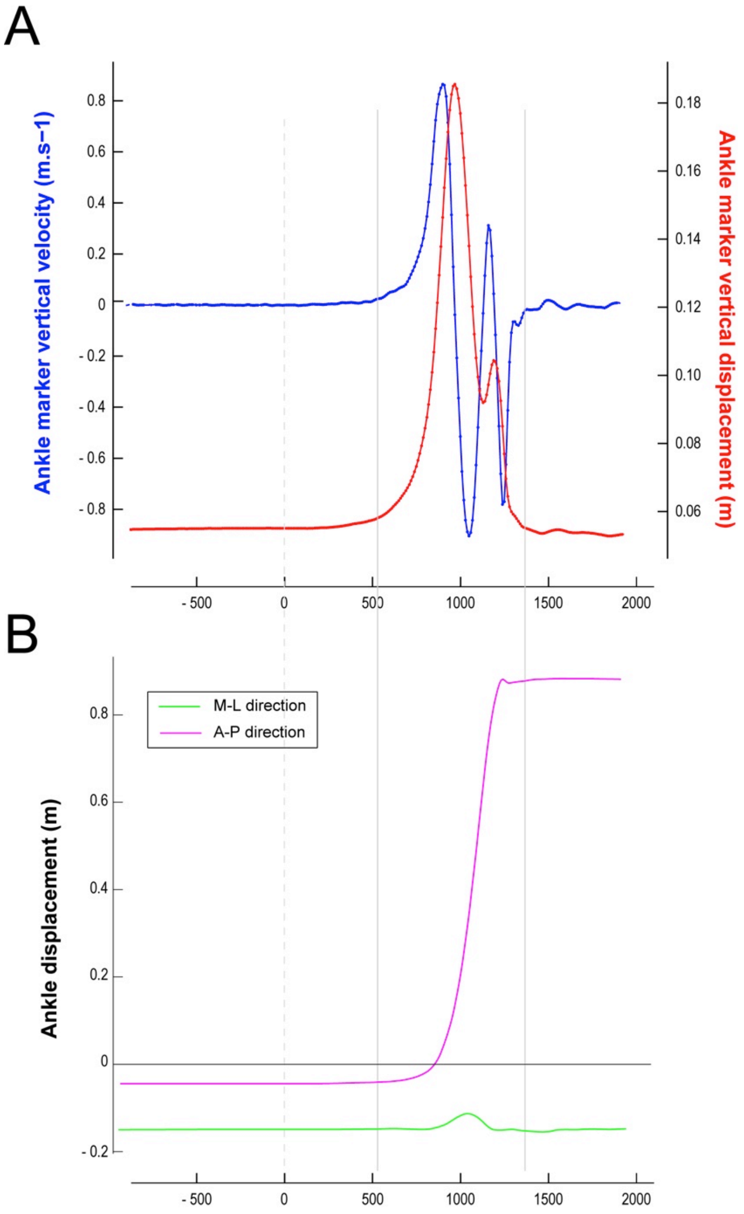


Figure 5: Determination of step characteristics. Representative example of vertical displacement of the malleolus of the stepping leg from which the step characteristics were determined. Time zero (dotted line) is onset of the perturbation. Solid gray lines are the onset and end of the step.

Landing Phase

The anterior-posterior impulse was calculated from the sum of the force plates where the first step foot landed until the second step. This result was then integrated over time. The velocity was calculated using the midpoint of the bilateral acromion markers, and then the velocity was multiplied by the subjects' mass for the momentum. The change in momentum and velocity are the difference between the first and second heel strike (figure 6).

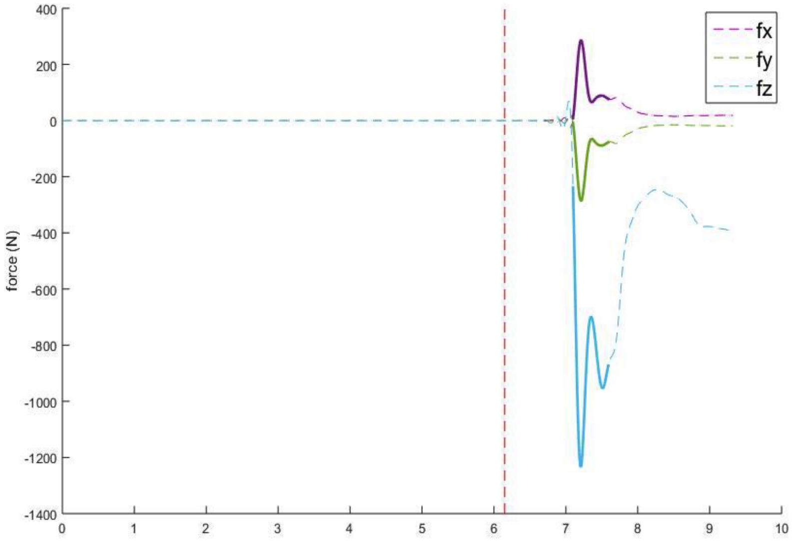


Figure 6: Determination of the landing impulse and momentum. Representative example of the landing impulse from the force plate where the first stepping foot landed. The regions used to calculate the landing impulse are highlighted in bold lines. The dotted vertical line is the onset of the perturbation.

Statistical Analyses

Descriptive statistics were used to describe the data for both groups and to assess distribution and equal variance. Normality of the distribution was tested using the Shapiro-Wilk test. Significant results on the Shapiro-Wilk and test for homogeneity of variance (Levene statistic) indicated the clinical measures were not normally distributed, and the variance was different between groups. In addition, an unequal number of stepping responses between groups and legs for each strategy of the induced step task was observed, requiring non-parametric analysis. The Mann-Whitney U-test was used to determine difference between groups. Difference between legs within each group was tested using a Wilcoxon signed-rank test. The Friedman test was used to identify difference between strategies for each leg. When there was a difference between strategies, the Wilcoxon test was used for post hoc with significance at $p<0.016$. Spearman's rho correlation was used to analyze the relationship between the clinical data and the induced step variables. Because of the variability of responses in the asymmetrical stepping strategies, only the EQ condition was used for the correlation. The IBM SPSS 23 was used for all statistical analysis, and $p<0.05$ was considered significant except in cases of post hoc.

Results

Stepping Strategy

All subjects stepped on all trials, however one control subject resisted the pull and did not step on the first trial. One trial was dropped from one poststroke subject and one control subject when they needed external assistance to regain their balance. Six of the 21 stroke subjects only used their non-paretic leg for stepping regardless of condition.

The asymmetrical standing postures were intended to facilitate stepping with paretic leg in stroke. In the dominant standing posture (DO), subjects stood with 70% of their body weight on the dominant leg (or non-paretic in the stroke group) and they could initiate steps with either the leg that was bearing most of the body weight (i.e., dominant or non-paretic leg) or the leg that was bearing only 30% of their body weight (i.e., the nondominant or paretic leg). In the nondominant standing posture (ND) the opposite occurred: 70% of the body weight was on the nondominant leg (or paretic leg in the stroke group) and steps could be initiated with either the leg that had more weight on it (the nondominant or paretic leg) or the leg that was more unloaded (i.e., the dominant or non-paretic leg). Thus, for each asymmetrical standing posture (DO and ND) there were two possible stepping responses, stepping with the leg that was bearing 70% of their body weight (loaded step - LS) or the stepping with the leg that was bearing only 30% body weight (unloaded step - ULS). The aim of the study was to investigate the similarities and differences in the stepping response therefore the data was grouped by type of step for each leg and group. The type of step strategies used were asymmetrical loaded step strategy (LS), when the subject stepped with the leg supporting most of body weight, and asymmetrical unloaded step strategy (US), when the subject stepped with the mostly unloaded leg (Appendix D).

Across both asymmetrical strategies both stroke and control subjects utilized more ULS than LS. There was a significant difference between group for the percentage of steps taken with their dominant leg for the equal strategy (EQ) condition (U=23.5, Z=-4.44, p=.000), LS (U=46, Z=-3.88, p=.000), and ULS (U=109.5, Z=-2.398, p=.017) (table 2).

% Steps with Dominant/non-Paretic leg	Control Mean (median)	Stroke Mean (median)
Equal WB steps (EQ)^	33.1 (30)	86.2 (100)
Loaded step (LS)^	7.6 (0)	56.0 (67)
Unloaded step (ULS)*	80.4 (90)	97.1 (100)

Table 2: Stepping strategies by group. *Indicates significant difference between groups, p<0.05. ^ indicates p<0.0001.

Stroke subjects initiated steps with their paretic leg more often with ULS ($\overline{x}$ = 44%, Md = 33%) as compared with mean of 14% (Md = 0) in equal weight-bearing and only mean of 3% (Md = 0) of the trials in the LS. Based on the Friedman test there was significant difference between strategies (X^2 (*2*)=27.88, p=.0001), with post hoc revealing a significant difference between EQ and ULS (Z=-3.41, p=.001) and LS and ULS (Z=-3.41, p=.001), but not significant difference between EQ and LS (Z=-2.21, p=.027) (figure 7).

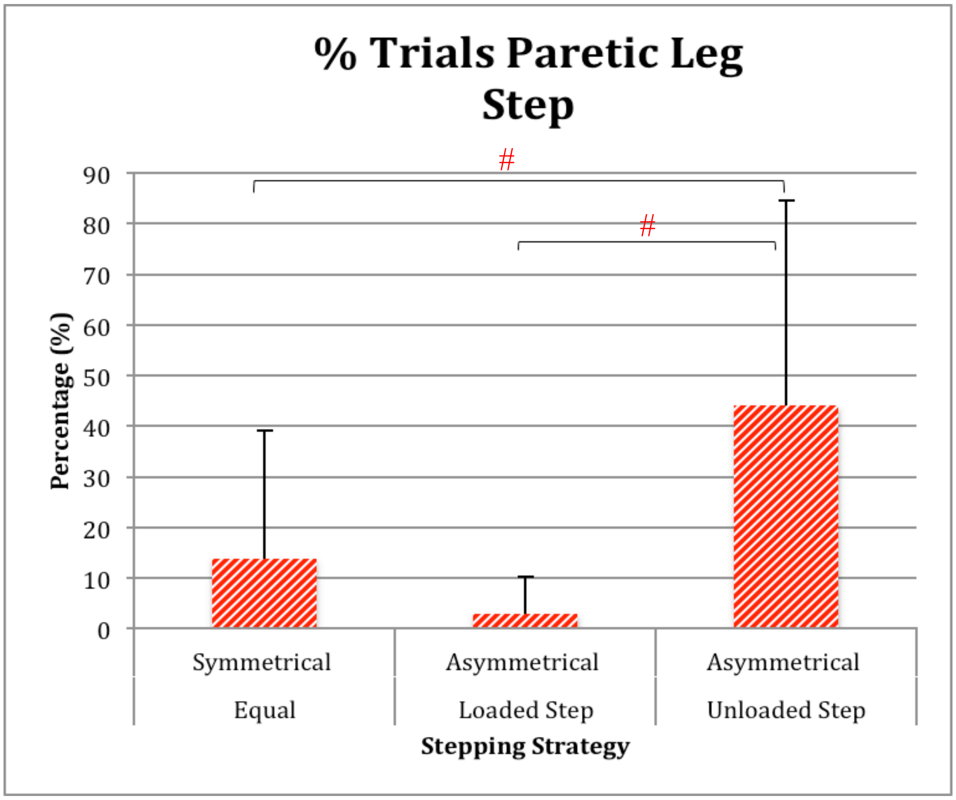


Figure 7: Mean percentage of trials with paretic leg stepping. # indicates significant difference between groups, p<0.016.

Preparation Phase: Anticipatory Postural Adjustments (APA)

Twenty of the 38 subjects (six controls or 35.3%, and 14 stroke or 66.7%) had at least one trial with no APA. No APA trials occurred in 3% of all control trials and 6% of all stroke trials. Most of the no APA trials occurred with the ULS (49%), with only 16% with the LS, and 35% in the EQ condition.

Type of step	Control	Stroke	Combined
Equal WB	46.7%	30.6%	35%
Loaded step (LS)	13.3%	16.7%	16%
Unloaded step (ULS)	40%	52.8%	49%

Table 3: Percentage of no APA trials

In the EQ strategy, APA onset was significantly earlier in stroke subjects compared to controls for stepping with the non-paretic leg (U=35, Z=-2.96, p=.003) and paretic leg (U=25, Z=-2.19, p=.028). The same result was observed in ULS with non-paretic leg (U=81, Z=-2.67, p=.008) and the paretic leg (U=70, Z=-2.17, p=.03). However, no difference was found between controls and stroke subjects in the LS strategy. There were no differences between legs for stroke or control groups for any of the stepping strategies (EQ, LS, ULS) (figure 8).

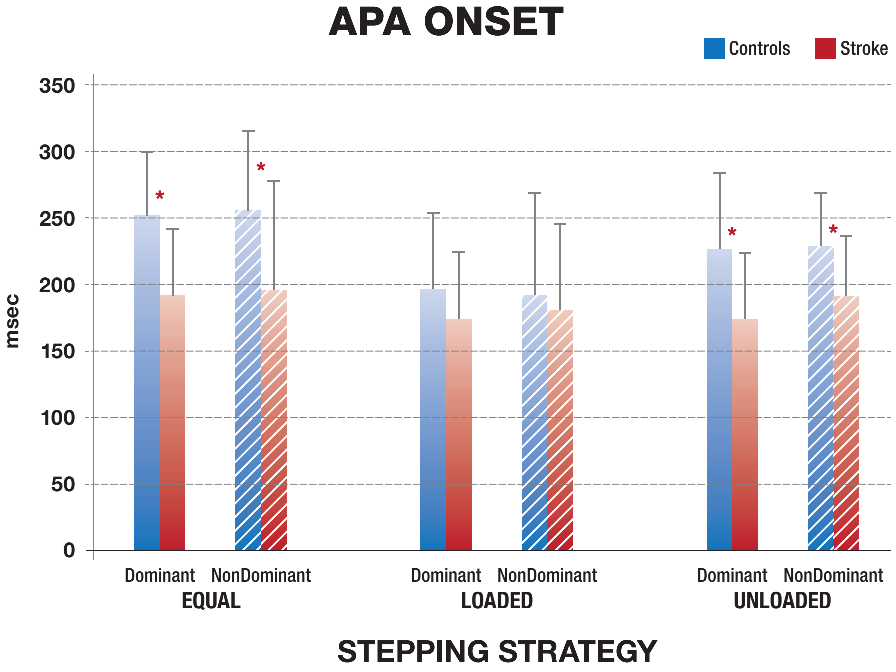


Figure 8: Anticipatory Postural Adjustment (APA) onset. * indicates significant difference between groups, p<0.05.

The peak amplitude of the APA before the step was significantly larger in the stroke group compared to controls only for steps taken with nondominant paretic leg in the EQ strategy (U=21, Z=-2.45, p=.014). It did not reach significance in the nondominant paretic leg LS strategy (U=2, Z=-1.65, p=.099). No other significant differences were found between groups and no difference between legs (figure 9).

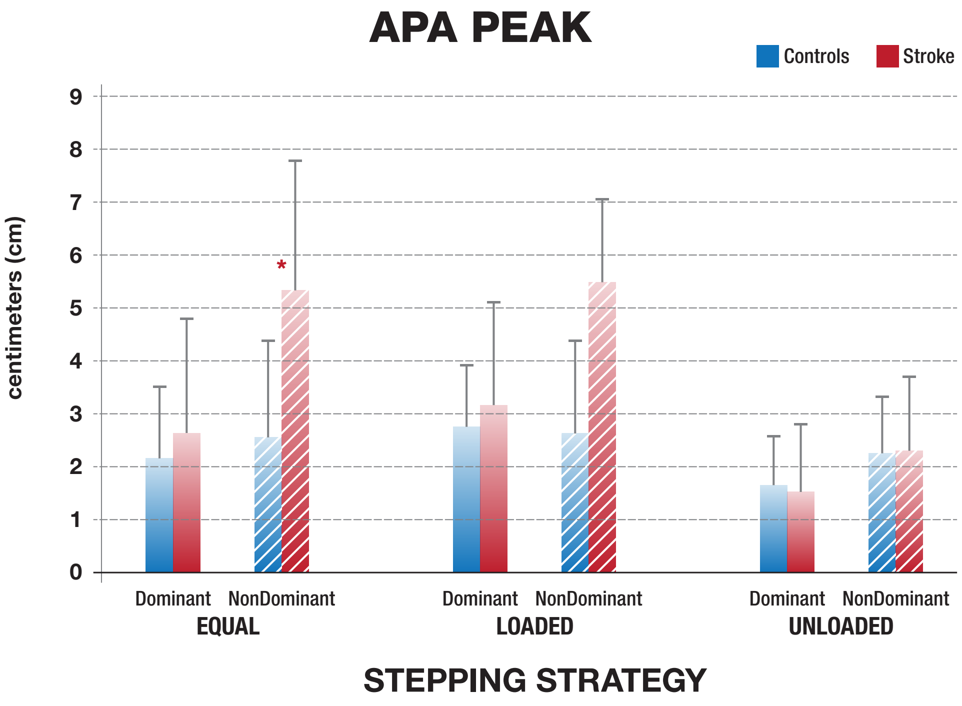


Figure 9: Anticipatory Postural Adjustment (APA) peak. * indicates significant difference between groups, p<0.05.

There was no difference in APA duration between groups or between legs for either group (figure 10).

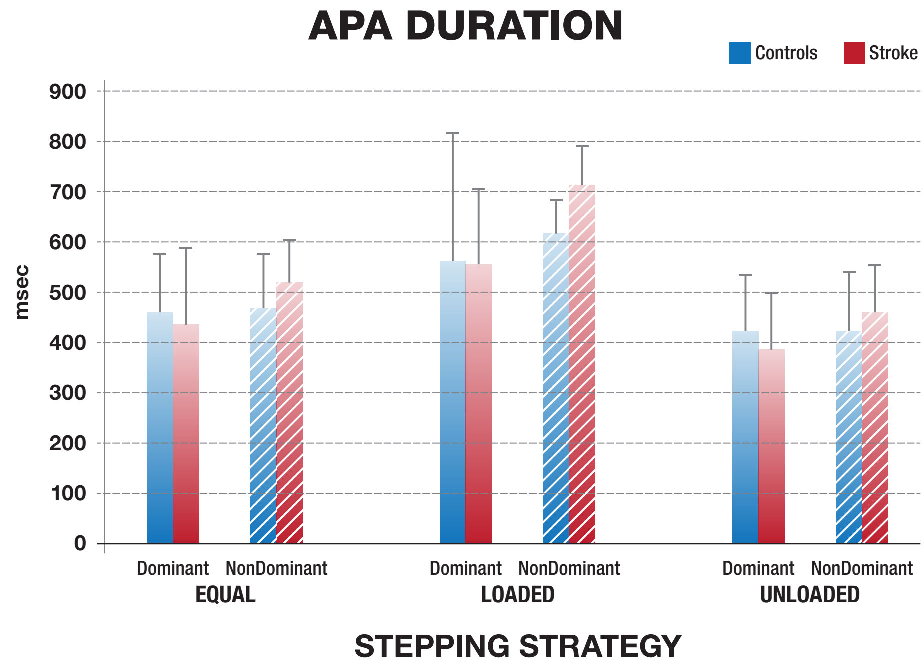


Figure 10: Anticipatory Postural Adjustment (APA) duration. No significant difference between groups or legs p>0.05.

<u>Execution Phase: First Step Characteristics</u>

Consistent with the hypothesis, stroke subjects took significantly more steps than controls to recover their balance, whether using their paretic (U=9.5, Z=-3.31, p=.001) and non-paretic leg (U=48, Z=-2.7, p=.007) in the EQ strategy or using their nondominant paretic leg (U=35.5, Z=-3.57, p=.0001) and dominant non-paretic leg (U=75.5, Z=-2.9, p=.004) in the ULS strategy. The number of recovery steps was not significantly different between controls and stroke in the LS strategy when initiating a step with the dominant non-paretic leg (U=15, Z=-1.8, p=.072) and almost reach significance with the nondominant paretic leg (U=6, Z=-1.96, p=.051). In the stroke group the paretic leg took significantly more steps than the non-paretic leg in the EQ condition (Z=-1.99, p=.046) and with the ULS strategy (Z=-2.49, p=.013) only (figure 11).

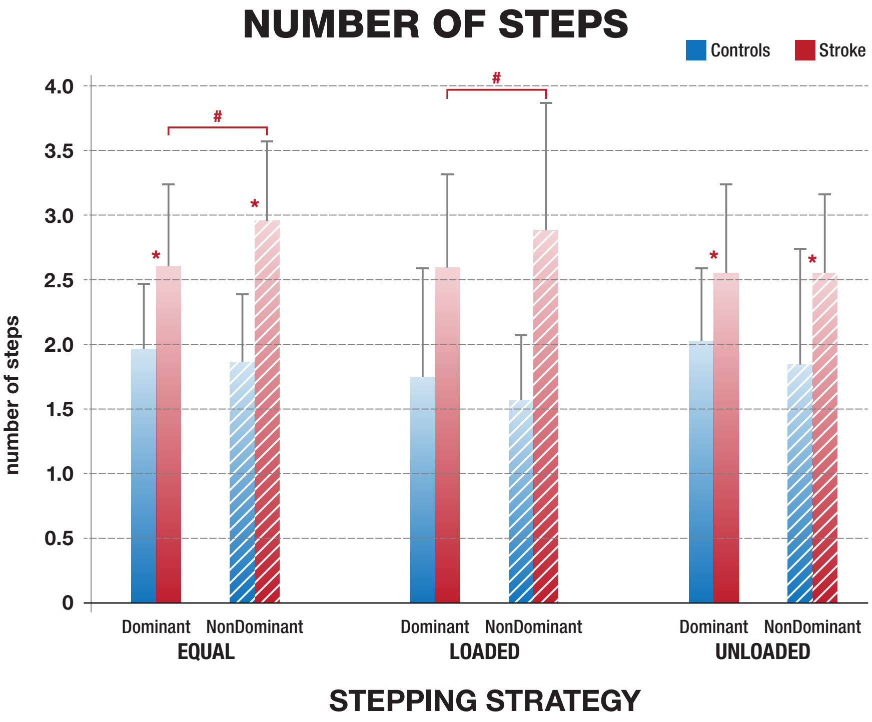


Figure 11: Number of steps. * indicates significant difference between groups and # indicates significant difference between legs, p<0.05.

Step onset was earlier for the dominant non-paretic leg in stroke compared to control, however this was only significant in the ULS strategy (U=87, Z=-2.48, p=.013). The step onset was much later for the nondominant paretic leg in the LS strategy (823 ms), but it was not significant due to the larger standard deviation and small number of subjects who used this strategy (Z=-1.34, p=.180). There was no significant difference between legs in either group (figure 12).

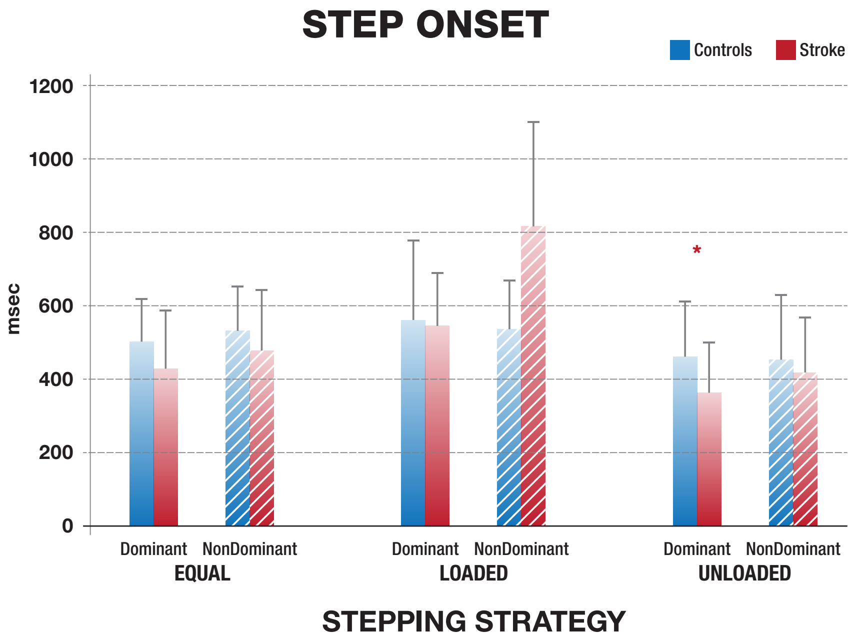


Figure 12: Step onset. * indicates significant difference between groups, p<0.05.

Step duration was longer when stepping with the nondominant paretic leg for stroke group compared to controls in the EQ strategy (U=24, Z=-2.25, p=.024), LS strategy (U=3, Z=-2.32, p=.021), and ULS strategy (U=73, Z=-2.06, p=.040). The dominant non-paretic leg step duration was shorter in stroke compared to controls but only significantly different in the ULS (U=84, Z=-2.58, p=.01). Not surprisingly, step duration was significantly longer in the paretic leg compared to the stronger non-paretic leg for the stroke group in the EQ (Z=-2.37, p=0.018) and ULS (Z=-3.07, p=.002) strategy. Although step duration was longer for the paretic leg in the LS type, the differences were not significant (Z=-1.34, p=.180). There was no difference between legs in controls (figure 13).

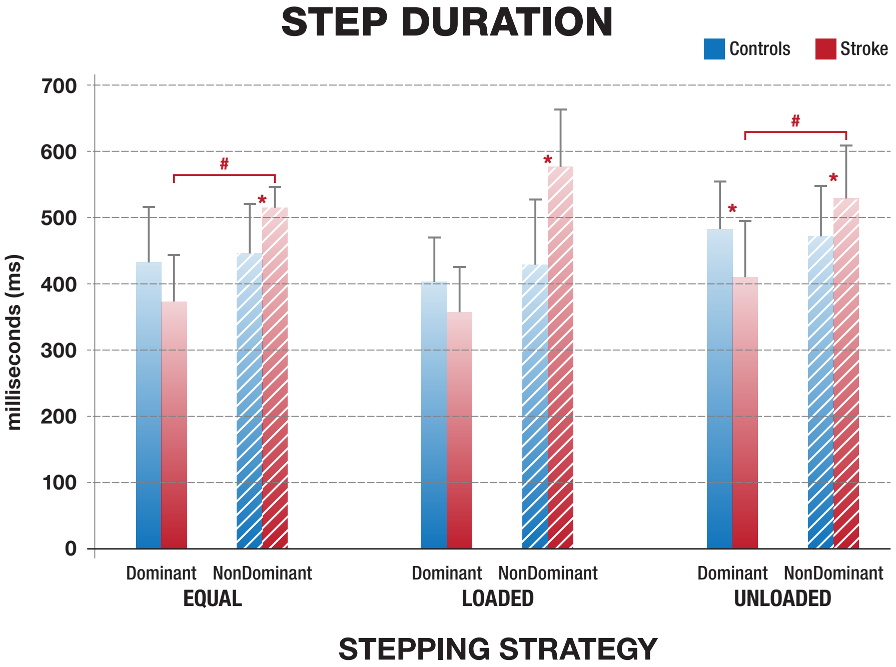


Figure 13: Step duration. * indicates significant difference between groups, and # indicates significant difference between legs, p<0.05.

Step length was significantly shorter for the stroke subjects compared to controls when stepping with the dominant non-paretic leg in EQ (U=59, Z=125, p=.025) and ULS (U=72, Z=-2.94, p=.003) strategies and when stepping with the nondominant paretic leg in the ULS (U=68, Z=221, p=.025). There was no significant difference between legs for either stroke or controls (figure 14).

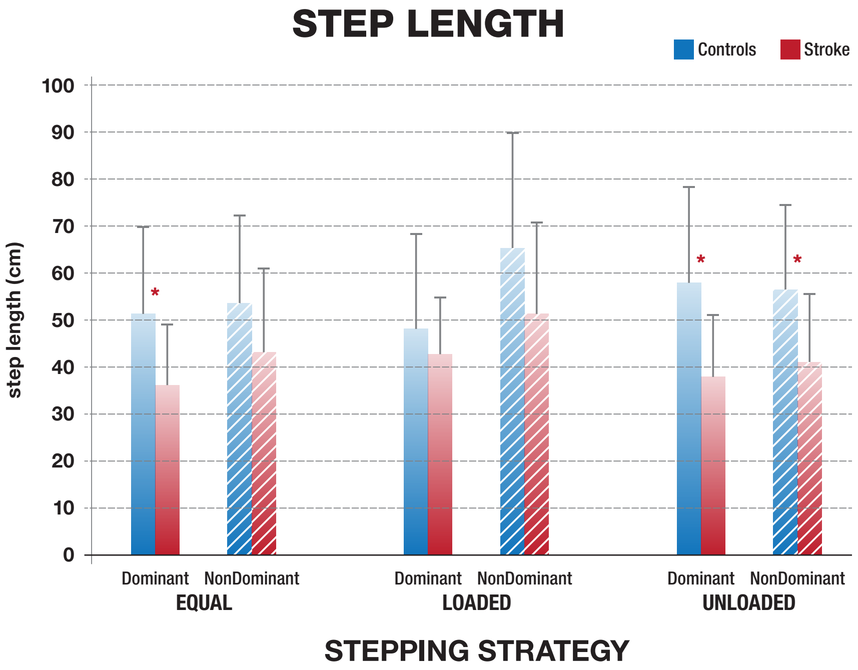


Figure 14: Step length. * indicates significant difference between groups, p<0.05.

No significant difference was found between groups for step width for the EQ strategy nondominant leg (U=41, Z=-1.18, p=240) or dominant leg (U=70, Z=-1.81, p=.071), for the LS strategy nondominant leg (U=12, Z=-.926, p=.355) or dominant leg (U=736 Z=.00, p=1), or for the ULS strategy nondominant leg (U=104, Z=-.887, p=.375) or dominant leg (U=149, Z=-.582, p=.56). No difference was found between legs for either group (table 4).

STEP WIDTH						
Step Strategy	Symmetrical **Equal**		Asymmetrical **Loaded**		Asymmetrical **Unloaded**	
Controls	Dominant	NonDominant	Dominant	NonDominant	Dominant	NonDominant
Mean	0.01635	0.00266	0.00991	0.01148	-0.00406	0.00337
SD	0.01683	0.02202	0.08309	0.03173	0.03505	0.04936
Median	0.01518	-0.00250	0.00559	0.01259	-0.01477	0.02613
Stroke	Dominant NonParetic	NonDominant Paretic	Dominant NonParetic	NonDominant Paretic	Dominant NonParetic	NonDominant Paretic
Mean	-0.00003	0.02230	0.00489	0.04432	-0.01019	0.00260
SD	0.03038	0.04029	0.04776	0.05080	0.04504	0.03081
Median	-0.00471	0.02202	0.01207	0.06559	-0.01530	0.00213

Table 4: Mean, standard deviation (SD), and median for step width.

There was no difference between groups for step height with EQ paretic (U=34, Z=-1.62, p=.105) and non-paretic (U=87, Z=-1.13, p=.258), LS paretic (U=14, Z=-.617, p=.537) and non-paretic (U=24 Z=-1.02, p=.307, and ULS paretic (U=87, Z=-1.53, p=.126) and non-paretic (U=142, Z=-.797, p=.425). No difference was found between legs for either group (figure 15).

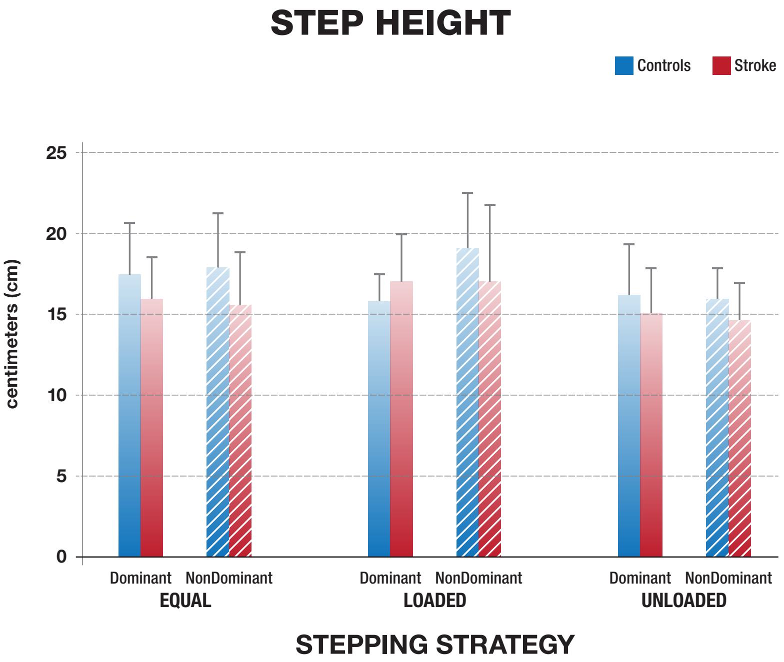


Figure 15: Step height. No significant difference between groups or legs p>0.05.

Landing Phase: Termination

Twenty stroke subjects were used in the landing analysis. One subject poststroke was not included due to missing markers. Stroke subjects were moving significantly slower than controls at heel strike, but this was only significant in the UL strategy with the nondominant paretic (U=69, Z=-1.99, p=.047) and dominant non-paretic leg (U=93, Z=-2.13, p=.033). There was no difference between legs for velocity at heel strike for either group (figure 16).

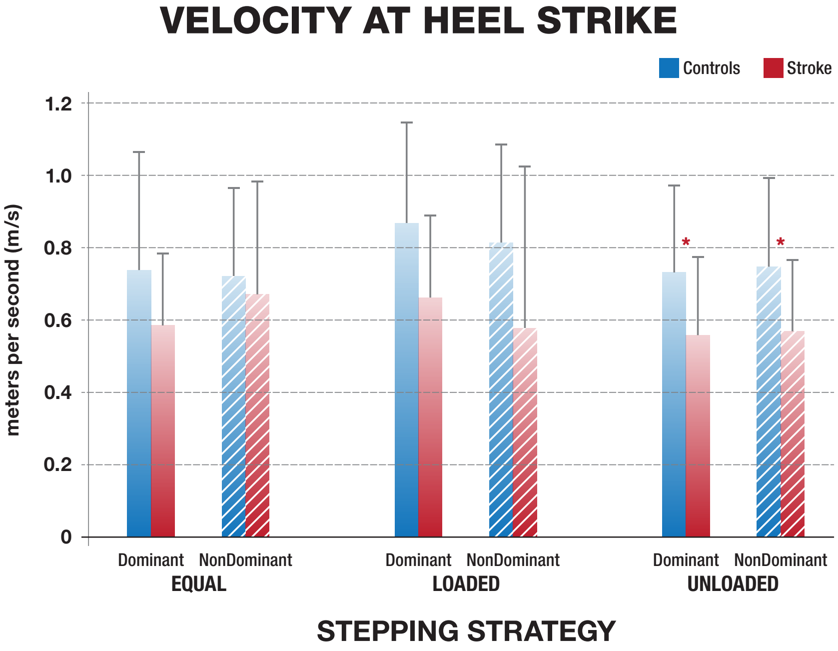


Figure 16: Velocity at heel strike. * indicates significant difference between groups, p<0.05.

Anterior-posterior landing impulse was larger in the controls compared to the stroke group but only significantly for the EQ strategy when stepping with the nondominant paretic leg (U=38, Z=-2.08, p=.038) only. There was no significant difference between legs for landing impulse in the stroke group but a significant difference between legs in controls for the EQ weight-bearing (Z=-2.04, p=.041) (figure 17).

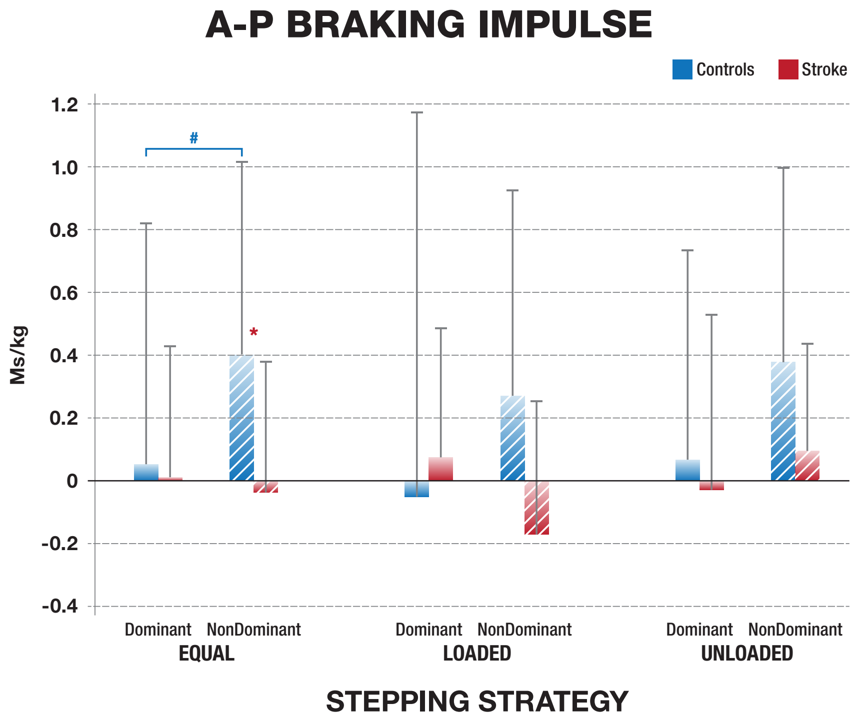


Figure 17: Landing impulse. * indicates differences between groups, # indicates differences between legs, p<0.05.

Stroke subjects showed significantly less change in momentum compared to controls when stepping with the paretic leg in the EQ strategy (U=29, Z=-2.56, p=.01), LS (U=3.0, Z=-2.6, p=.009) and ULS strategy (U=46, Z=-2.99, p=.004). Change in momentum was significantly less in the stroke group when stepping with the nondominant paretic leg compared to the dominant non-paretic leg in the ULS (Z=-2.67, p=.008), and almost reaching significance in the EQ (Z=-1.96, p=.051). No difference was found for change in momentum between legs in controls (figure 18).

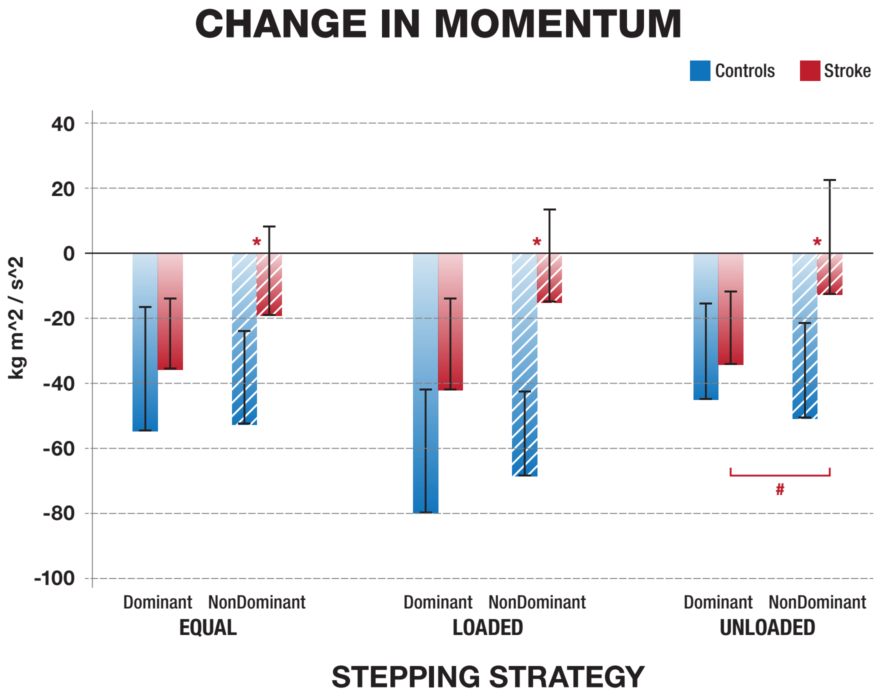
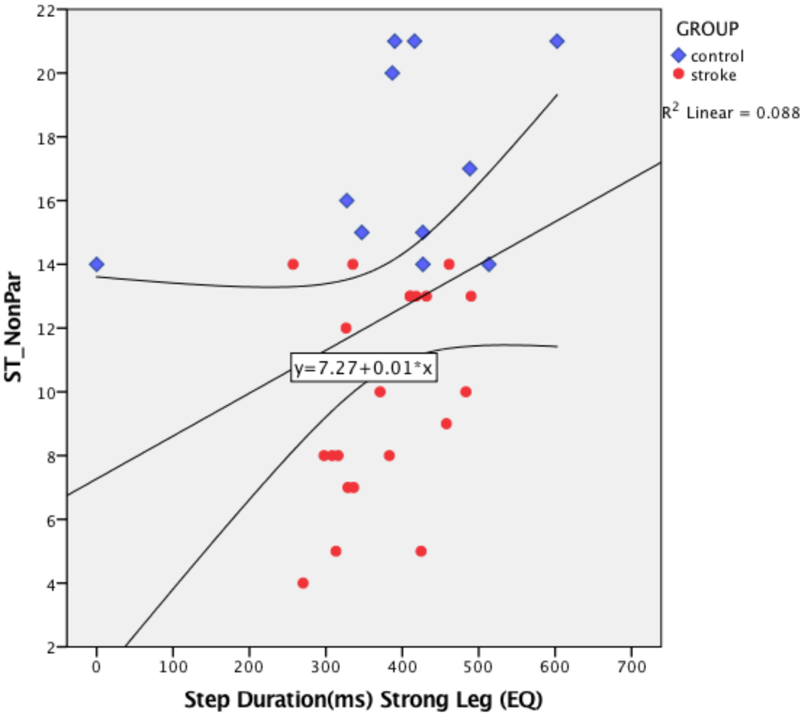


Figure 18: Change in momentum. * indicates differences between groups, # indicates differences between legs, p<0.05.

Induced Stepping Variables to Clinical Measures

Correlations were studied to identify any potential associations between selected stroke specific-related clinical outcome measures and perturbation-induced step characteristics. The variables used for the correlations were: a) UMCe measuring lower extremity motor control and representing the body structure function domain with force at landing in the landing phase; b) Step Test representing the activity domain with step duration in the execution phase; and c) the ABC representing the participation domain with the number of steps in the execution phase. A Spearman's correlation showed no significant correlation between lower extremity motor control (UMCe) and landing impulse for the paretic/non-preferred leg (r_s = -.298, n=26, p=.139) or the non-paretic/preferred leg (r_s =.047, n=32, p=.798). A significant but weak correlation was found for the score on the Step Test with the dominant leg and the step duration for the dominant leg in the EQ step strategy (r_s = .364, n=32, p=.04) indicating better dynamic balance was weakly associated with a greater amount of time spent in unilateral support (figure 19). A weak negative correlation was also found between the ABC score and the number of steps for the EQ condition (r_s = -.409, n=38, p=0.011) indicating lower balance confidence is weakly associated with the need for more steps after a perturbation (figure 20).

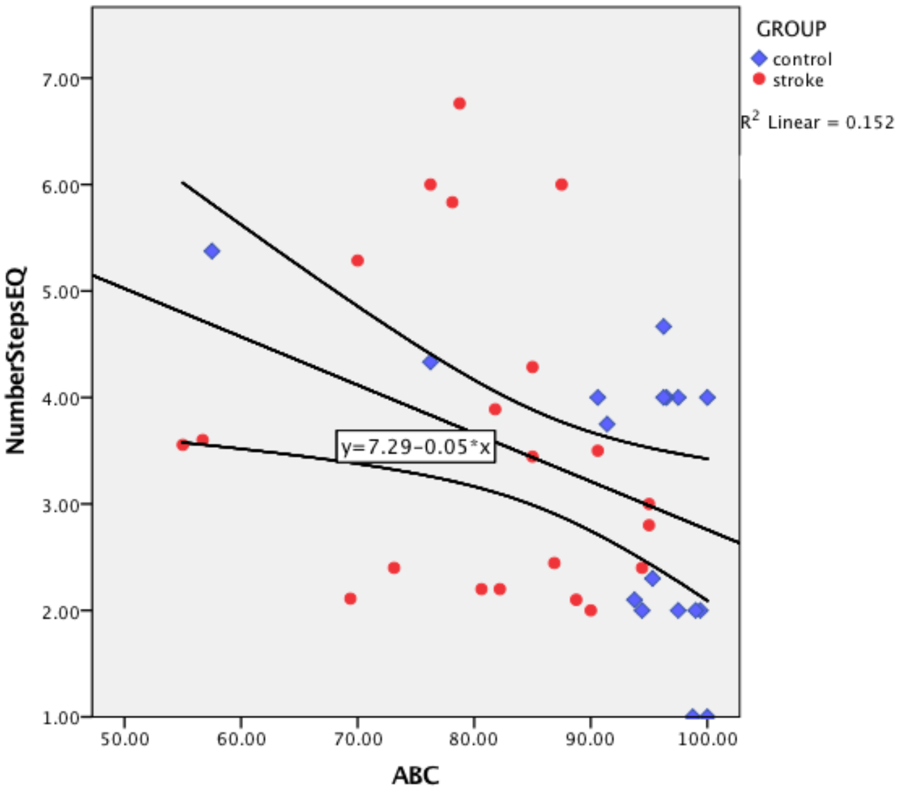


Correlations

			ST_NonPar	Step Duration(ms) Strong Leg (EQ)
Spearman's rho	ST_NonPar	Correlation Coefficient	1.000	.364*
		Sig. (2-tailed)	.	.040
		N	38	32
	Step Duration(ms) Strong Leg (EQ)	Correlation Coefficient	.364*	1.000
		Sig. (2-tailed)	.040	.
		N	32	32

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 19: Correlation for dominant leg Step Test (ST) and step duration for symmetrical equal (EQ) step strategy.



Correlations

			ABC	NumberSteps EQ
Spearman's rho	ABC	Correlation Coefficient	1.000	-.409*
		Sig. (2-tailed)	.	.011
		N	38	38
	NumberStepsEQ	Correlation Coefficient	-.409*	1.000
		Sig. (2-tailed)	.011	.
		N	38	38

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 20: Correlation for Activities-specific Balance Confidence scale and mean number of steps in the symmetrical equal (EQ) step strategy.

Chapter 5: Discussion

Introduction to the Chapter

The purpose of this study was to investigate the differences in perturbation-induced protective stepping in stroke survivors and age- and gender-matched controls at three phases of the stepping response, preparation, execution, and landing. This chapter will discuss the key findings and implications of the results. Suggestion for potential impact on postural control training and assessment of balance will be discussed. Limitations of the study and areas of further research are also identified.

Discussion

The need for a reactive stepping in everyday life is sudden and necessitates producing an appropriate movement of the limb to the catch the moving center of mass (COM) within a new base of support (BOS). This has been an identified issue for older adults with impairments in sensorimotor function due to the aging process. Impaired sensorimotor function and asymmetry of movement and stepping are common issues for stroke survivors. The unexpected nature of perturbations in everyday life does not always allow time for selection of the leg to use.

Previous studies report a predilection for initiating a reactive-induced protective step with the non-paretic leg in stroke survivors.[21,27,107] In this study, although there was a preference for stepping with the non-paretic leg, the unloaded step strategy (ULS) significantly increased the percentage of times the stroke group initiated their reactive step with their paretic leg compared to the equal step strategy (EQ) and loaded step strategies (LS). Initiating an induced protective step with the paretic leg required more steps but was as effective as stepping with the non-paretic leg given that the only fall that occurred in this stroke group was when the non-paretic leg initiated the step. Whether an individual poststroke initiates steps with their paretic or non-paretic leg after a perturbation, the coordinated use of both limbs are needed to bring the moving COM back over a newly configured BOS. Therefore given the asymmetry of function that is typical poststroke, consideration should be given to the capabilities and responses of both legs. The finding of this study suggest that there are differences between stroke and controls not only in leg selection but also in the preparation, execution, and landing of the protective step in both legs. Clinicians should then include both limbs in postural control training.

Preparation Phase

The absence of anticipatory postural adjustment (APA) during induced protective stepping has been reported by others in non-impaired adults and stroke.[19,21,50,88,108] It is not surprising that more of these trials occurred with ULS strategy when the weight transfer had already occurred. For the stroke group this may contribute to the earlier step onset in the ULS. In addition, a larger percentage of subjects in the stroke group did not utilize an APA compared to controls. This is similar to the smaller number of APA trials in older versus younger adults during induced stepping and may reflect increased instability and uncertainty of initiating a protective step.[23,88,109,110]

The earlier APA onset in stroke compared to controls is somewhat different than reports in older and younger adults for induced stepping.[23,88,109] McIlroy et al.[109] reported later APA onset in the older subjects compared to the younger, but Schultz et al.[88] found the younger adults had a later onset than the balance-impaired older adults, while Rogers et al.[23] found no difference in APA onset between younger and older subjects. The earlier APA onset found in this study may reflect the stroke group's instability to the perturbation and/or a decision to step rather than to wait. Previous work has shown that older adults step more often and at smaller perturbation than younger adults.[22,50,111] Traditionally this was thought to be due to ineffective feet-in-place strategies,[112] but other work has shown that reactive stepping often occurs well before the limits of stability have been reached even with smaller perturbations in less-stable older adults.[22,28,50,51,111] This implies that less-stable individuals such as older adults as well as stroke survivors may trigger an earlier response to a perturbation.

A large peak in the paretic leg has not been reported in voluntary gait initiation[30,105] or in voluntary leg flexion,[59] however these studies did not control for the initial position of the COM. The symmetrical stance position in this study may have contributed to the larger APA peak during paretic leg stepping compared to control. Increasing the load on the swing limb prior to gait initiation was found to enhance swing limb loading during the APA in younger and older adults, and persons with Parkinson's, while another study showed a strong correlation (r=.95) of initial swing leg loading with peak APA in stroke subjects.[33,113] Marigold et al. showed that increasing the load on the paretic limb increased the magnitude of the medial gastrocnemius muscle activation with backward surface perturbation reflecting a greater postural reflex.[34] In non-impaired individuals a greater ground reaction force was found when stepping with the nondominant limb during gait initiation.[114] The difference in APA peak for the paretic leg compared to controls in the symmetrical EQ step strategy may indicate a different strategy for the preparation of foot lift off during reactive protective stepping when in a symmetrical stance position. Clinicians could potentially train induced stepping from a symmetrical standing posture to enhance the preparatory response and improve the postural response on the paretic leg.

Execution Phase: Step Characteristics

Multiple stepping responses after a perturbation are reported to occur more often in older adults and fallers than in younger subjects, even in the lateral direction.[25,26,50,88,109] Multiple steps are thought to indicate an ineffective stepping response through the inability to control the COM over the new base of support and increasing the risk of falls.[24] All the subjects poststroke in this study took multiple steps. Multiple steps after an anterior perturbation in stroke may be needed due to the asymmetrical lower extremity function. Given the average number of steps in this group of stroke survivors was greater than 2.5 steps regardless of stepping leg, expecting stroke survivors to recover their balance after an anterior perturbation with less than two steps may be unrealistic. However, the subjects in this study were not instructed to limit their steps, therefore their actual capacity to stop their forward momentum with less steps is unknown.

In this study more steps were taken when initiating the induced-protective stepping response with the paretic leg. We hypothesized that this finding was related to decrease in motor control of the paretic legs poststroke, however no correlation was found between the number of steps and lower limb UMCe test ($r_s = .053$, n=38, p=.754). It is possible that lower extremity extension strength as measured by the UMCe is not directly related to the number of steps taken or that the limited number of ordinal levels in the UMCe constricted the results. Lower balance confidence was weakly related to the number of steps and suggests that those who feel less confident or less stable when perturbed will take more steps. The need for greater number of steps in stroke may relate to what occurs after the step is executed, such as in the landing phase.

A significantly earlier step onset for the stroke group when stepping with the dominant non-paretic leg only occurred in the UL step strategy. In this situation the stroke subjects had to maintain postural control when there was increased weight on their weaker paretic leg, which is not a typical standing position. Earlier step onset is consistent with earlier onset in older compared to younger adults.[26,50,88] This earlier step onset after the perturbation may indicate greater instability or fear of falling given the difference in ABC scores found in this study. It may also be indicative of a learned behavior that stepping in response to the perturbation is more effective than a feet-in-place response.[23] This perspective is consistent with other studies that have shown that reactive induced steps are often taken well before the limits of stability exceed the BOS.[22,28,51,111] The lack of differences in step onset between groups in the EQ strategies may be surprising given the earlier APA onset for this strategy. The longer APA duration in the EQ compared to the ULS strategy (Z=-2.69, p=.007) may account for the lack of difference in step onset for the EQ strategy.

The longer step duration for the nondominant paretic leg compared to controls most likely reflects the impaired motor control of the paretic limb given the difference in the UMCe between groups. The longer step duration and the relatively shorter step length of the paretic leg in the stroke group may put the COM more anterior at foot contact when stepping with that leg. This could contribute to the need for additional steps.

Differences in perturbation-induced stepping between stroke and controls for both the paretic and non-paretic legs illustrate the complexity of bipedal postural control of the COM when two limbs vary in neuromuscular control. In a study using backward perturbations, stroke subjects had more difficulty getting their COM back within their BOS compared to controls.[107] The smaller induced step duration and length of the non-paretic leg in this study could be related to greater instability during unilateral stance on the weaker paretic leg. After a perturbation, if the stronger non-paretic leg is stepping, the weaker paretic leg must support and control the body mass unilaterally until the opposite stepping foot lands on the ground. This may lead to a shorter step. Also, if the weaker paretic leg is stepping, it must lift off the ground quickly and get into an appropriate location to catch the COM. Stepping with either leg after a perturbation appears to be challenging for ambulatory stroke survivors.

Asymmetry of gait initiation is observed clinically and has been reported in the literature;[30-33] therefore, differences between paretic and non-paretic legs for step duration and number of steps were not surprising. The lack of difference in the first step length and height may be the result of the unexpected standardized anterior pull assisting in the forward weight shift of the COM regardless of the stepping leg. It may also reflect the capacity of the paretic leg for stepping that is not seen in voluntary stepping. However the lack of difference may be from a shorter lower step with the non-paretic leg due to the desire to get off the paretic leg.

Landing Phase: Termination

Gait termination requires the coordinated effort and activity of both legs to arrest the forward momentum and maintain postural control.[115,116] Typically the leading leg generates most of the braking force by creating an extensor thrust through a strong burst by the plantar flexors, knee extensors, and hip extensors.[117] The trailing limb shows a strong dorsiflexion burst to reduced push-off and a reduced AP GRF compared to the leading limb.[117] Terminating forward body movement in one step requires the leading limb to generate a large enough braking impulse to reduce the forward momentum created by the perturbation to zero. If the leading limb is unable to generate a sufficient braking impulse additional steps will be required. The diminished braking impulse of the paretic leg compared to controls is probably related to the impaired ability to generate extensor thrust given the difference in scores on the UMCe for the paretic leg. In addition, the shorter step length observed in the stroke group may have reduced their ability to produce a posterior directed ground reaction force. As step length is decreased, the biomechanical advantage to create a collision with the floor and dissipate the forward momentum is reduced.[118] Learning to take a longer induced step response would create a biomechanical advantage for slowing the body momentum, especially for the weaker leg.

The lack of difference in braking impulse between paretic and non-paretic legs may be related to the need for a coordinated muscular activation pattern between both legs.[117] In a study with individuals with Parkinson's Disease and controls, the Parkinson's group displayed a smaller braking impulse, diminished EMG activity of the TA and GM on the stepping leg, and no change in the timing of the muscle activity in the trailing leg.[119] The authors concluded the combined contributions of both the stepping and trailing limb contributed to the difference in braking impulse seen in these two groups. The impairments in DF range and neuromuscular control (UMCe) of the paretic leg may have interfered with the overall braking impulse when it was the trailing leg. This illustrated the importance of considering the contributions of both legs in the landing phase of protective stepping regardless of which leg is the leading limb.

It was not surprising that the change of momentum was greater for the control group given the velocity at heel strike was larger. However, the only significant difference in speed between groups was in the UL strategy. Even though the stroke group was slower at heel strike, they needed significantly more steps to stop their forward momentum. The significant difference in change in momentum between groups for the paretic leg especially for the EQ strategy and LS strategy where the velocity at heel strike was not significantly different may explain the need for the greater number of steps taken by the stroke group. In addition, the later step onset in the paretic LS may have positioned the COM more anterior at heel strike, interfering with the biomechanical alignment to generate a braking impulse. This preference for utilizing the non-paretic leg for the initial step after a perturbation may be related to the ability of the paretic limb to slow and stop the forward momentum. Choosing to step with non-paretic leg even if it is loaded (LS, dominant non-paretic) may delay step onset compared to stepping with the paretic leg that is more unloaded (UL, nondominant paretic), but appears to allow for a more effective approach for stopping the body.

Differences Between Legs

The lack of difference between legs for induced step onset, length, APA, and landing impulse in the stroke group is surprising given the asymmetry that is seen clinically in gait and is reported during gait initiation by others.[30,32,33,120] This may be a result of controlling the initial stance symmetry posture in this study. As reported by others, weight-bearing asymmetry can have an impact on postural control,[121,122] and when weight bearing was controlled there was no difference between legs in stroke subjects.[34] It would be reasonable to assume that difference in the step duration and change in momentum on the paretic side was due to impaired neuromuscular control of the paretic limb especially given the larger number of steps taken. However the similarities in UMCe scores between legs in the stroke group and the lack of correlation of lower extremity motor control with number of steps implies that other factors may be related to this difference.

The difference between legs in the controls for the landing impulse was unexpected. Previous studies showed no difference in performance between legs during static single limb standing balance tasks in healthy adults.[103,104] Two studies reported no significant preference for stepping leg in non-impaired healthy young adults during perturbations. [122,123] While the dominant leg was not the preferred stepping limb, the authors did report a clear bias within subjects for a preferred perturbation-induced protective stepping leg.[123]

Although these studies report no difference between legs, footedness or leg dominance has been studied.[124-128] Limb dominance is used to express the preferential use of one limb for voluntary movement[102,124] and is often based on the two different functions or tasks, mobilization and stabilization the leg or foot must perform,. Mobilization refers to voluntary motor control such as kicking a ball accurately or writing a name in sand with the foot, both of which requires specific neuromuscular control of the distal leg and foot. Stabilization movements such as standing on one leg relate to support of the body and require more proximal muscle control.[102,124] Reactive stepping after a perturbation require both skilled movements, getting the foot quickly into a proper position and supporting the body weight. Symmetry in able-bodied gait is also often assumed, but differences between legs have been identified.[102 129]

During gait initiation APA duration and center for gravity displacement was higher in the preferred limb of ten right-hand/leg young adults, while the velocity at heel strike was lower.[130] Asymmetries in the frontal plane were also seen with step width, trunk lean, M-L COP, and the total impulse during gait initiation in 34 healthy males.[114] In these studies the authors concluded that asymmetry or normal limb preference does play a role in controlling the body motion and should be differentiated from asymmetry due to postural impairments. The results of this current study support the conclusion that there may be a variance in lower limb performance for postural control,[131] but the link to leg preference may be related to the asymmetry of the role (mobilization or stabilization) the limb is required to play.[132] During reactive protective stepping the legs must perform both roles depending on the number of steps taken and the leg that initiates the step. Again, training of both legs would be beneficial to allow adaptive responses in both limbs.

Implications and Recommendations

Reactive stepping is a complex task that should be part of every stroke balance-training program as it requires the coordinated use of both limbs to maintain upright control. Training should include initiating steps with both the paretic and non-paretic limb. This study has shown that unloading the paretic leg will increase the likelihood of initiating the induced step with that leg. This can be done through use of asymmetrical standing posture or passively with a diagonal pull away from the paretic leg as done in a previous study.[21] The diagonal pull can facilitate the lateral weight shift as well as the release of the paretic leg step. First step termination requires the leading leg to generate a larger braking force by creating a strong extensor thrust through activation of the plantar flexors, knee and hip extensors. Attempting to stop the forward momentum of the body leading with the paretic leg would be a functional approach to strengthen and reinforce the less common paretic step strategy in stroke survivors.

Increasing probability of utilizing a paretic leg in response to a perturbation will give the stroke individual more options for maintaining upright control. Given the unexpected nature of a perturbation in everyday life and the typical asymmetrical stance that is often used by poststroke survivors, training should consider the initial standing posture. Encouraging loaded steps with the paretic leg would challenge both the postural adjustment needed to initiate the step as well as potentially build and reinforce an alternative strategy to the common non-paretic leg step. Progressive training can be accomplished by modifying the angle of pull and or by increasing the weight on the paretic leg may enhance this stepping ability and carry this new movement pattern to everyday life.

Limitations and Delimitations

The limitations and delimitations of this study should be considered as we interpret and apply the results of the study clinically to the stroke population. First, this study investigated only anterior perturbations in chronic stroke survivors, therefore the direction was known to the subjects, and after the first perturbation the intensity was not novel. This may have allowed the subjects to prepare and minimized the unexpected nature of the reactive response. This was addressed by randomizing the hold time prior to the perturbation trials.

Falls in the community-dwelling stroke survivors occur frequently in standing and walking.[2] This study addressed balance response to perturbation in standing only. We can speculate how this may apply during gait given the asymmetrical standing posture but are limited to the similarities in the early stance phase of gait. The lack of correlation with the lower extremity motor control probably indicates more sensitive measures of motor control may be needed to detect any potential relationship. The impact of sensorimotor limitations on stepping response would be interesting and outside the aim of this study.

This study included chronic stroke survivors who ambulated independently in the community, and who on average were 9-years post stroke. The results can only be generalized to stroke survivors with similar characteristics. Although all participants lived independently in the community, there was a variety of orthosis and assistive device use, and we did not control for sensorimotor function. Therefore, this sample is quite heterogeneous in presentation. To allow for a more natural response to the perturbation in each of the stance symmetry postures, we did not specify which leg the subject was to use for stepping. This created unequal number of responses within subjects and across subjects and strategies. Increasing the number of subjects or controlling for stepping response may address this issue in future studies.

Future Research

Modifying human motor behavior is difficult, and postural control is complex; thus, it is not surprising there are number of factors that require further investigation. First, is it feasible to reduce the predilection for stepping with the non-paretic leg and enhancing the effectiveness of the paretic leg when it is used in response to a perturbation? Would step training in stroke survivors decrease the number of steps needed to maintain upright control or increase the use of the paretic leg? One case study of an individual post stroke reported increased use of the non-preferred limb by physically blocking the leg but no change in the non-blocked trials was seen even as the weight bearing shifted off the stepping leg.[85]

Future research should also identify what type of training would be most effective in preventing falls poststroke. Should training address the underlying impairments of strength and range, or could task-specific induced step training address both impairments and altered movement patterns? If induced reactive stepping is improved, is there an impact on voluntary gait since both tasks require an active stepping response of the lower limb? More importantly, does the ability to use the paretic leg for induce reactive stepping impact quality of life and risk of falls in community dwelling stroke survivors?

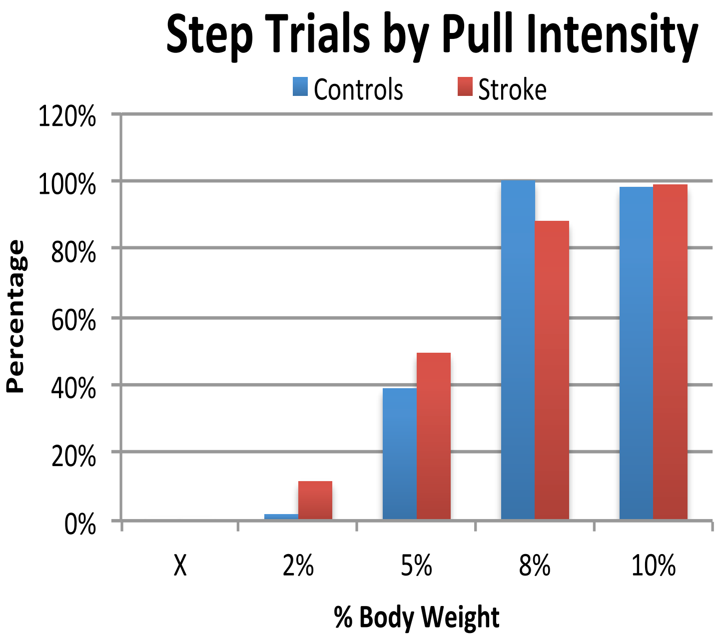
Further investigation of joint powers in the landing phase of induced stepping may assist in understanding the potential ability of individuals with asymmetrical impairments of their lower extremity to improve their reactive stepping performance. At this time it appears that the asymmetry of sensorimotor impairments may be a factor for stepping response after a perturbation, but given the differences seen between controls and the non-paretic leg in stroke, a closer look at the performance of this extremity in reactive postural control needs further examination.

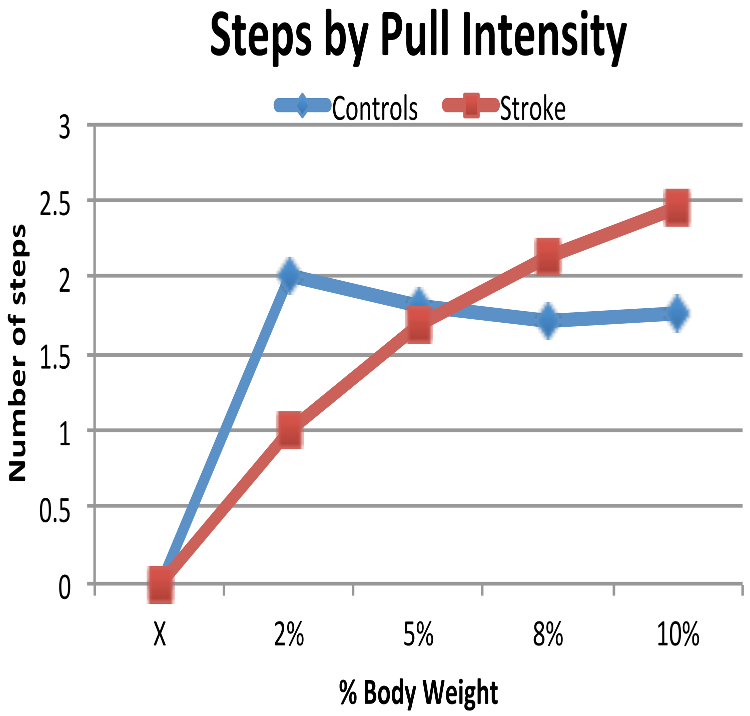
Lastly, difference in perturbation-induced stepping has been reported between younger and older adult. Although most stroke occur after age 65[36,41] 34% of hospitalizations for stroke in 2009 were younger than 65.[133] In this study we controlled for age between groups however difference between younger and older adults post stroke should be investigated to further clarify factors that should be considered in reactive balance training.

Conclusion

This study identified some important differences between chronic stroke survivors and controls for perturbation-induced protective stepping that should be considered in designing treatment interventions for reactive postural control in stroke. Stroke subjects required more steps than controls regardless of which leg initiated the step. Unloading the paretic leg prior to perturbation onset can reduce the predilection for stepping with the non-paretic leg. When stepping with their non-paretic leg, the stroke survivors were significantly different compared to age-matched controls in APA onset, step duration and length, and velocity at heel strike. These differences imply that effective training of reactive postural control in stroke should not focus solely on induced protective steps with the paretic leg. The coordinated use of both extremities is important for reactive postural control and is linked to the release of the protective step that is probably different than voluntary gait initiation and should be considered.

Appendix A: Results of pilot study to determine perturbation intensity





Appendix B: Phone screen form

3. Phone Screen Form

Interviewer Name:______________________

Subject last name first:____ Date____________

Subject phone number:_____________________

1. What is your approximate height and weight? (must be less then 300lbs and 6ft 6 in)
2. Was this your only stroke?_____________ Yes **No**

3. When was your stroke?_____________ (greater than 12 months ago) Affected Side: Right Left

- Do you know what type of stroke you had? _______________________________________

4. Do you use a wheelchair? **Yes** No

5. Are you able to walk independently in the community Yes **No**
If yes, how far can you walk?_____________________

a) Do you wear a brace on your weak leg when you walk (AFO)? Yes No
If yes, all the time? _____________________________
Is it plastic or metal?_____________________________
Is it hinged? Yes No

b) Do you use an assistive device when you walk? Yes No
(ie: SLC, 2ww, 4ww, quad cane, etc.) If yes, what kind? ______________________________

d) Do you use your brace and cane when you are in the house? **Yes** No
If yes, all the time?
How far do you walk without brace/cane in house?

6. Do you have any serious medical conditions (vestibular, neurological, or musculoskeletal)? Yes No
Have you had any surgery and when? Yes No
Do you experience any dizziness? Yes No
Do you have any other types of neurological diagnosis (CP, MS, Parkinson's) Yes No
Have you had any fractures? Of what, and when? Yes No
Do you have Diabetes or are you pre-Diabetic? Yes No

7. Do you have significant pain that interferes with your ability to go about your daily activities? Yes No

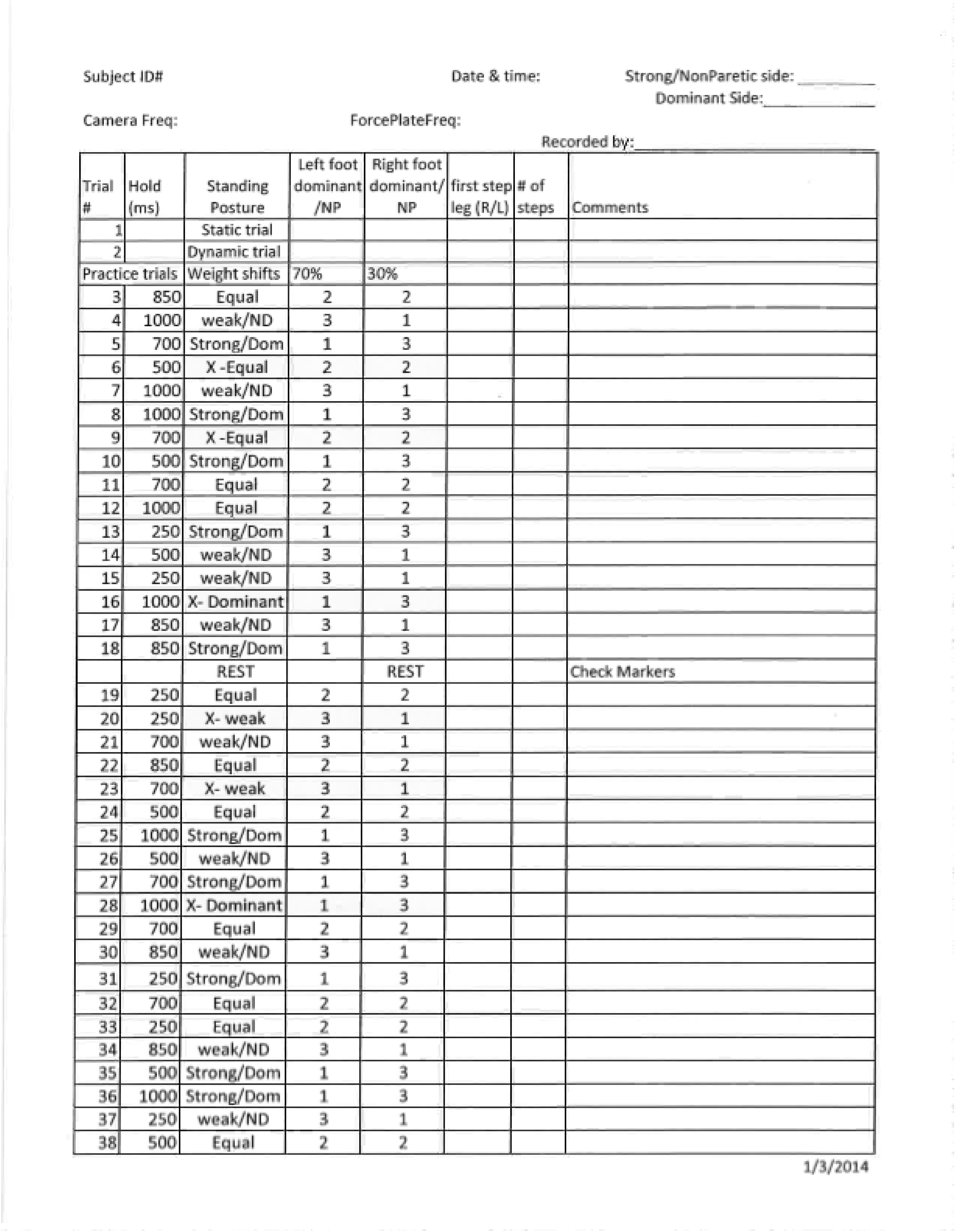
8. This study will ask you to stand and will challenge your balance without your brace and cane. Are you willing to do that?

9. Are you currently participating in any type of stroke therapy? Yes No
Which therapy? _________________________________

Comments: email / Date and time scheduled

Revised 1-13-14, km

Appendix C: Data sheet



Subject ID#

Date & time:

Strong/NonParetic side: _________

Dominant Side:____________

Camera Freq:

ForcePlateFreq:

Recorded by:_______________________

Trial #	Hold (ms)	Standing Posture	Left foot dominant /NP	Right foot dominant/ NP	first step leg (R/L)	# of steps	Comments
1		Static trial					
2		Dynamic trial					
Practice trials		Weight shifts	70%	30%			
3	850	Equal	2	2			
4	1000	weak/ND	3	1			
5	700	Strong/Dom	1	3			
6	500	X -Equal	2	2			
7	1000	weak/ND	3	1			
8	1000	Strong/Dom	1	3			
9	700	X -Equal	2	2			
10	500	Strong/Dom	1	3			
11	700	Equal	2	2			
12	1000	Equal	2	2			
13	250	Strong/Dom	1	3			
14	500	weak/ND	3	1			
15	250	weak/ND	3	1			
16	1000	X- Dominant	1	3			
17	850	weak/ND	3	1			
18	850	Strong/Dom	1	3			
		REST		REST			Check Markers
19	250	Equal	2	2			
20	250	X- weak	3	1			
21	700	weak/ND	3	1			
22	850	Equal	2	2			
23	700	X- weak	3	1			
24	500	Equal	2	2			
25	1000	Strong/Dom	1	3			
26	500	weak/ND	3	1			
27	700	Strong/Dom	1	3			
28	1000	X- Dominant	1	3			
29	700	Equal	2	2			
30	850	weak/ND	3	1			
31	250	Strong/Dom	1	3			
32	700	Equal	2	2			
33	250	Equal	2	2			
34	850	weak/ND	3	1			
35	500	Strong/Dom	1	3			
36	1000	Strong/Dom	1	3			
37	250	weak/ND	3	1			
38	500	Equal	2	2			

1/3/2014

Appendix D: Step strategies

Symmetrical
Equal step
strategy
EQ

Asymmetrical
Loaded step
strategy
LS

Asymmetrical
Unloaded step
strategy
ULS

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