Reactive balance control after stroke: Towards enhanced clinical understanding and assessment

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Abstract

Safe and independent mobility is a primary rehabilitation goal for those with stroke, of which balance control is a key determinant. The risk of falls post-stroke is high and fall rates rise dramatically soon after discharge from the hospital. Previous research has revealed the essential role that reactive balance control, specifically the capacity to initiate and execute a rapid step, has in preventing falls. Of concern, reactive balance control is not routinely assessed within physical therapy practice. Challenges to clinical assessment may include a lack of available methods that are safe, standardized and able to quantify and characterize balance responses. Therefore, this dissertation aimed to advance understanding of reactive stepping after stroke to inform and guide clinical assessment practices. The present findings affirmed that reactive stepping post-stroke is a significant problem not clearly revealed by commonlyused clinical measures that focus on voluntary control, thereby, supporting the need to develop targeted assessments of reactive balance control. Further, the findings revealed the potential for clinical uptake of alternate approaches, specifically the lean-and-release method, to assess reactive stepping among those in early stages of stroke rehabilitation. When paired with kinetic measurement technology, such approaches were able to quantify and reveal determinants of temporal dyscontrol of both the paretic and nonparetic lower-limbs, known to be associated

with falls after stroke. Further work is warranted to evolve the lean-and-release assessment towards a more useful clinical tool, suitable for widespread clinical uptake.

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Table of contents

Abstract		ii
Acknowledg	ements	iv
Table of Con	tents	v
List of Table	S	vii
List of Figure	2S	vii
List of Abbre	eviations	viii
Chapter 1: I	ntroduction	1
. 1.1	The importance of advancing clinical practices in stroke rehabilitation	2
1.2	Impact of impaired balance after stroke	2
1.3	Balance control: current concepts	4
1.4	Reactive balance control strategies	5
1.5	Reactive balance control after stroke	6
1.6	Reactive stepping: a critical link to falls in daily life	8
1.7	Training reactive stepping to reduce fall risk	9
1.8	Balance assessment: current clinical practice	11
1.9	Integrated knowledge translation	14
1.10	Summary	15
1.11	Research Objectives	16
Chapter 2: In	npaired reactive stepping among patients ready for discharge from inpatient	47
stroke rehat	bilitation	1/
2.17	ADSTRACT	18
2.21	Acthed	19
2.31	2.2.1 Setting and participants	21
	2.3.1 Setting and participants	22
	2.3.2 Protocol for reactive stepping assessment	22
	2.3.5 Medsules	25
2.4.1	2.5.4 Data allalysis	20
2.41	2 / 1 Participants	27
	2.7.1 a tripping maired stenning responses	27
	2.4.2 Relationshin to clinical measures	21
251		33
Chapter 3: C	linical implementation of a reactive balance control assessment in a sub-acute	
stroke patie	nt population using a 'lean-and-release' methodology	39

3.1 Abstract	40
3.2 Introduction	41
3.3 Method	42
3.3.1 Setting and participants	42

	3.3.2 Lean and release methodology
	3.3.3 Measures
	3.3.4 Data analysis
3.4	Results
	3.4.1 Clinical use and implementation
	3.4. 2 Patient specific determinants of reactive balance control assessment
3.5	Discussion
3.6	Conclusions
hapter 4:	Reactive stepping after stroke: comparing paretic and nonparetic time to foot off
4.1	Abstract
4.2	Introduction
4.3	Methods
	4.3.1 Setting and participants
	4.3.2 Measures
	4.3.3 Data analysis
4.4	Results
	4.4.1 Participant profile
	4.4.2 Reactive TFO in the paretic and nonparetic lower limb
	4.4.3 Determinants of TFO in the paretic and nonparetic lower limb
	4.4.4 Step initiation and consequences for assessment-induced 'falls'
4.5	Discussion
4.6	Conclusion
Chapter 5:	General Discussion
Chapter 5: 0 5.1	General Discussion Summary of Findings
2 hapter 5: 0 5.1	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control
Chapter 5: 0 5.1	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of
Chapter 5: 0 5.1	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping
2.1 (Chapter 5: 0) (Chapter 5: 0) (C	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol
Chapter 5: (5.1	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess
Chapter 5: 5.1 5.2 rea	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control
Chapter 5: 0 5.1 5.2 rea	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol
Chapter 5: 0 5.1 5.2 rea	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping
Chapter 5: 0 5.1 5.2 rea	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method.
Chapter 5: 5.1 5.2 rea	 General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol
Chapter 5: 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol. 5.2.1.4 Perturbation amplitude
5.1 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol 5.2.1.4 Perturbation amplitude 5.2.1.5 Instructions
5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol 5.2.1.4 Perturbation amplitude 5.2.1.5 Instructions 5.2.1.5 Pre-perturbation limb load
5.1 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol 5.2.1.5 Instructions 5.2.1.5 Pre-perturbation limb load 5.2.1.7 Clinically meaningful measures of reactive stepping
Chapter 5: 0 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol 5.2.1.5 Instructions 5.2.1.5 Pre-perturbation limb load 5.2.1.7 Clinically meaningful measures of reactive stepping 5.2.2 The patient
Chapter 5: 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol. 5.2.1.5 Instructions 5.2.1.5 Instructions 5.2.1.7 Clinically meaningful measures of reactive stepping 5.2.2 The patient. 5.2.2 The patient.
Chapter 5: 0 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method 5.2.1.3 Tasks and conditions to expose balance dyscontrol. 5.2.1.4 Perturbation amplitude 5.2.1.5 Instructions 5.2.1.7 Clinically meaningful measures of reactive stepping 5.2.2 The patient 5.2.3 The therapist 5.2.4 The practice setting
Chapter 5: 0 5.1 5.2 rea	General Discussion Summary of Findings 5.1.1 The need for targeted measures of reactive balance control 5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping 5.1.3 Measurement approaches to reveal underlying temporal dyscontrol Key considerations for the evolution and clinical uptake of new approaches to assess ctive balance control 5.2.1 The innovation: Evolution of the clinical assessment protocol 5.2.1.1 The goal of the clinical assessment of reactive stepping 5.2.1.2 The perturbation method. 5.2.1.3 Tasks and conditions to expose balance dyscontrol. 5.2.1.5 Instructions 5.2.1.5 Pre-perturbation limb load. 5.2.1.7 Clinically meaningful measures of reactive stepping. 5.2.2 The patient. 5.2.3 The therapist 5.2.4 The practice setting

References 10	.04
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List of tables

Table 2.1	Clinical profile of patients by category of reactive stepping ability	28
Table 2.2	Frequency of participants who exhibited impaired reactive stepping performance across unconstrained and encouraged-use conditions	30
Table 3.1	Clinical profile of patients who received a lean-and-release reactive balance control assessment (REACT) versus those who did not (NoREACT) during inpatient stroke rehabilitation	50
Table 4.1	Characteristics of 105 individuals with stroke who completed a reactive stepping assessment at time of discharge from inpatient rehabilitation	70
Table 4.2	Multivariate regression analyses to determine associations with paretic and nonparetic time to foot off during reactive stepping assessment	72

List of figures

Figure 2.1	The 'lean-and-release' balance perturbation method	24
Figure 2.2	Scatterplot of individual participant Berg Balance Scale scores and walking speed values by sub-group of reactive stepping ability	32
Figure 3.1	The 'lean-and-release' balance perturbation method	44
Figure 3.2	Distribution of scores for those who received the reactive balance control assessment (REACT) versus those who did not (NoREACT) on measures of functional balance, disability and mobility	51
Figure 4.1	Distribution of of mean paretic and nonparetic limb time to foot off (TFO) values for 105 individuals with stroke who completed a reactive stepping assessment at time of discharge from inpatient rehabilitation	71
Figure 5.1	The Knowledge-to-Action framework	86
Figure 5.2	Determinants of clinical uptake of new assessment approaches	88

List of abbreviations

ADLs	Activities of daily living
ABC	Activities-specific Balance Confidence Scale
APAs	Anticipatory postural adjustments
BBS	Berg Balance Scale
BOS	Base of support
%BW	Percentage of body weight
CIS	Change-in-support
COVS	Clinical Outcome Variables Scale
CMSA	Chedoke-McMaster Stroke Assessment Impairment Inventory
СОМ	Centre-of-mass
ENC	Encouraged-use
FIM-T, M, C	Functional Independence Measure (total score, motor, cognitive sub-scores)
FIP	Feet-in-place
КТА	Knowledge-to-action (referencing a knowledge translation framework)
LOS	Length of stay
NoREACT	Patient group who did not receive a reactive stepping assessment
PREF	Preferred-response
REACT	Patient group who received a reactive stepping assessment
STRATIFY	St. Thomas Risk Assessment Tool
TFO	Time to foot off

Chapter 1: Introduction

1.1 The importance of advancing clinical practices in stroke rehabilitation

Every year, approximately 50 000 people with stroke or transient ischemic attacks are treated in Canadian hospitals; this equates to one stroke in every ten minutes (Heart & Stroke Foundation 2015). The annual cost of stroke is approximately \$3.6 billion, accounting for health care costs and lost economic output (Public Health Agency of Canada 2009). Stroke is the leading cause of disability in adults, with approximately 315, 000 Canadians living with the effects of stroke (Public Health Agency of Canada 2011). The 2014 Stroke Report from the Heart & Stroke Foundation warns that, although gains have been made in stroke treatment, there are more stroke patients living with more complex needs and more strokes occurring at a younger age; inevitably, as the world's population is aging, the number of individuals living with stroke and associated disability will increase (Heart & Stroke Foundation 2014). It is, therefore, paramount that we continue to advance clinical practices early in stroke rehabilitation to optimize outcomes and minimize burden to both the health care system and the individual.

1.2 Impact of impaired balance after stroke

Balance is an essential feature of safe and independent performance of whole-body actions or functional tasks. Balance abilities post-stroke have been found to have impact on functional performance and recovery (Bohannon and Leary 1995; Fong et al. 2001), likelihood for return to independent living (Lin et al. 2001; Wee et al. 1999), physical activity levels (Alzahrani et al. 2012; Michael et al. 2005) and perceptions of handicap after discharge (Desrosiers et al. 2002).

Impaired balance is also a primary contributor to falls after stroke (Weerdesteyn et al. 2008). Falls can have significant physical and psychosocial consequences. Up to 28% of those with chronic stroke report an injury following a fall (Lamb et al. 2003) and the risk to sustain a fall-related hip fracture is greater, and mortality rates post-surgery almost doubled, as compared to healthy elderly populations (Chiu et al. 1992; Ramnemark et al. 1998). Many who experience a fall have low falls self-efficacy (Andersson et al. 2008; Belgen et al. 2006) and describe that fear of falling, fear of potential injury and/or fear of public embarrassment are pervasive daily concerns (Schmid et al. 2012). This leads to restricted participation in everyday activities as a self-imposed or caregiver-imposed strategy to manage and prevent falls (Forster and Young 1995; Mackintosh et al. 2005; Schmid et al. 2012). This reduced physical activity is of concern given the resultant de-conditioning (Potempa et al. 1996), potential increase in risk of recurrent stroke or cardiovascular events (Greenlund et al. 2002; Greenlund et al. 2005; Mouradian et al. 2002), and cyclical effects of further functional decline (van de Port et al. 2006).

The risk of falls is high across the phases of recovery: cited fall rates have been as high as 22% in acute care settings (Davenport et al. 1996) and 47% during inpatient rehabilitation (Mayo et al. 1990). However, fall rates upon return to home increase as high as 73%, with the majority of falls occurring within the first eight weeks following discharge from the hospital (Forster and Young 1995). It is possible, then, that we are not optimally identifying those at most risk, or preparing these individuals during their inpatient rehabilitation, for the challenges they will encounter upon return to the community (Weerdesteyn et al. 2008).

1.3 Balance control: current concepts

Balance control is a complex interaction of musculoskeletal and neural (sensory, cognitive and motor) systems that are organized to meet functional goals within the context of the environment (Horak et al. 2009; Shumway-Cook and Woollacott 2007). Specifically, information from sensory systems (e.g. visual, vestibular, somatosensory) related to postural orientation and the environment is integrated and interpreted by the central nervous system with reference to an internal body schema; the central nervous system formulates an appropriate response and motor strategies are rapidly and accurately activated to perform the appropriate movements to maintain posture (Frank and Earl 1990; Mancini and Horak 2010; Massion 1994).

Human balance control ultimately reflects the ability to regulate the relationship between the individual's centre-of-mass (COM) and the base of support (BOS) during activities of daily living (ADLs) (Horak et al. 1989b; Horak et al. 1989a; Maki and McIlroy 1997). One can further consider three broad classes of stability requirements (Geurts et al. 2005; Pollock et al. 2000; Weerdesteyn et al. 2008) or primary 'functional goals' (Mancini and Horak 2010) of balance control: i) the maintenance of specific postures wherein the COM is maintained within the limits of a fixed BOS (e.g. quiet stance) ; ii) the facilitation of voluntary movement wherein the COM is repositioned within an existing/constrained (e.g. reaching) or newly–established BOS (e.g. walking), and; iii) balance recovery to sudden postural perturbations, or displacements of the COM or BOS (e.g. slip, trip, push), with appropriately timed and scaled responses to maintain stability. The latter 'goal' of balance control, specifically reactive balance control, is the focus of this dissertation.

1.4 Reactive balance control strategies

Reactive balance control can be classified into two categories of responses: i) feet-inplace (FIP) responses and; ii) change-in-support (CIS) responses (Horak et al. 1997; Maki and McIlroy 1997). Traditionally, FIP responses referred to the strategies and associated muscle synergies that one might use to restore the COM to a position of stability within a fixed BOS, through body movement centered around the ankles (ankle strategy) or hips (hip strategy) (Shumway-Cook and Woollacott 2007). The ankle strategy is used most often when the perturbation to balance is small and the support surface is firm (Horak and Nashner 1986). The hip strategy controls the COM by producing large and rapid movements at the hip joints with antiphase rotations of the ankles (Horak and Nashner 1986; Shumway-Cook and Woollacott 2007). It is suggested that the hip strategy is used when the perturbation to balance is larger or faster, or when the support surface is compliant or smaller than the feet (for example, standing on a beam) (Horak and Nashner 1986). However, a greater degree of re-stabilization can occur with CIS strategies, where rapid limb movements (reactive step or reach-to-grasp) adjust the BOS to recapture the COM (Maki and McIlroy 1997). Initially, researchers believed there was a hierarchy of evoked strategies (Horak and Nashner 1986; Horak et al. 1989b) based on degree of instability. A CIS strategy was considered a 'last resort', used solely in response to largemagnitude perturbations when the limits of FIP responses were reached, and when perturbations moved the COM outside of the BOS (Nashner et al. 1989; Shumway-Cook et al. 1988). However, subsequent research has confirmed that CIS strategies, specifically reactive steps, are a prevalent response to regain stability, even with small perturbations where the COM remains within the limits of the BOS (Brown et al. 1999; McIlroy and Maki 1993a; Mille et

al. 2003), and a commonly-observed reaction to loss of balance in daily life (Holliday et al. 1990). Of significance, rapidly changing the BOS through a reactive step is the only recourse to regain stability when perturbations are of significant magnitude and might otherwise result in a fall or if the FIP reactions are ineffective possibly due to disordered control (Maki and McIlroy 1997).

The characteristics of reactive stepping are fundamentally different than voluntary stepping. Volitional steps are almost always preceded by an anticipatory postural adjustment (APAs); these APAs reflect a shift in mediolateral COP initially towards the swing limb to propel the COM towards the stance limb to enable stability at foot-off (MacKinnon et al. 2007). In contrast, APAs are often absent or truncated within a reactive step elicited by a novel perturbation (Burleigh et al. 1994; Maki and McIlroy 1997; McIlroy and Maki 1996b). Of most importance, reactive stepping is initiated and executed much faster than volitional stepping (Burleigh et al. 1994; McIlroy and Maki 1996b). In contrast to volitional stepping, where there is the opportunity to pre-plan the movement, successful execution of reactive steps involves rapid detection of the onset and characteristics of instability and the environmental constraints, and rapid initiation and execution of the step with sophisticated spatial control of the limb (Maki and McIlroy 2006).

1.5 Reactive balance control after stroke

Studies of FIP responses in those with stroke, compared to healthy controls, have demonstrated delayed muscle onset latencies (Badke and Duncan 1983; Di Fabio et al. 1986; Di Fabio and Badke 1988; Dietz and Berger 1984; Ikai et al. 2003; Marigold et al. 2004) and less coordinated patterns of lower-limb muscle activation (Badke and Duncan 1983; Di Fabio et al. 1986; Di Fabio and Badke 1988; Kirker et al. 2000). Those with chronic stroke who exhibited delays in muscle onset and intra-limb muscle activation (i.e. delays between distal and proximal muscle activation) during FIP responses were more likely to 'fall' in response to a perturbation-evoked laboratory assessment (Marigold and Eng 2006).

Early work by Harburn and colleagues (Harburn et al. 1995), exploring clinical methods to assess reactive balance control, revealed that community-dwelling individuals with stroke exhibited failed FIP responses and an inability to use successful stepping strategies at lower perturbation thresholds, as compared to healthy elderly. However, it is only within the past 5 years that research has emerged providing limited insights into the performance and characteristics of reactive stepping after stroke. Those with stroke in sub-acute (Lakhani et al. 2011a; Mansfield et al. 2012) and chronic stages of recovery (Martinez et al. 2013) are more likely to initiate reactive stepping responses with their nonparetic limb. Paretic-limb stepping is associated with greater paretic foot motor recovery and decreased pre-perturbation load on the paretic limb (Mansfield et al. 2012). Despite the preference to step with the less-affected limb, individuals with stroke may still require physical assistance (Lakhani et al. 2011a; Mansfield et al. 2011; Mansfield et al. 2013) or use multi-step responses to regain stability (Lakhani 2010; Mansfield et al. 2011; Mansfield et al. 2013; Martinez et al. 2013). Reactive stepping was executed faster than voluntary stepping across all phases (step onset, APA/limb unloading and swing time) in a small cohort of those with chronic stroke (Martinez et al. 2013). Across case studies, however, individuals within sub-acute stages of recovery revealed marked delays within the early unloading and foot-off phases of the stepping limb, which influenced overall delays in step execution (Lakhani 2010; Mansfield et al. 2011); delays in unloading phase were associated with abnormal mediolateral postural adjustments (Lakhani et al. 2011a) and limb-load asymmetry (Mansfield et al. 2011) prior to the step. For reference, documented mean time to foot off (TFO) values for individuals with stroke ranged upwards to 891 ms, compared to 95% upper confidence limits of 600 ms for healthy controls using the same cablepull/weight-drop method of balance perturbation (mean TFO 515 SD 127 ms; 95% Cl[430,600 ms]; n=11). In contrast, step onset latencies were preserved and swing times varied, being faster or slower, compared to healthy controls (Lakhani 2010). It is noteworthy that there is limited information on paretic limb timing within reactive stepping responses; for example, across case and cohort studies, there is only one reference to a paretic mean 'time to foot off' value (558 ms) (Lakhani et al. 2011a). Further research to aid in understanding of reactive balance and, specifically, stepping performance and underlying dyscontrol is obviously warranted.

1.6 Reactive stepping: a critical link to falls in daily life

Reactive stepping performance has an important role in preventing falls. Within the community-dwelling elderly, prospective studies have demonstrated that, in response to anterior/posterior perturbations, the tendency to take multiple steps (more than one step) to recover balance is predictive of increased risk for falling forwards or backwards, and the tendency to follow the initial reactive step with a lateral step is predictive of increased risk of falling laterally in daily life (Maki et al. 2001). In response to mediolateral perturbations, stepping performance including limb collisions (Maki et al. 2001) and multiple stepping responses (Hilliard et al. 2008), and neuromusculoskeletal factors including trunk rotation and

hip abductor torque (Hilliard et al. 2008), were also predictive of increased risk of falls in daily life.

Recent studies have also confirmed that characteristics of reactive stepping performance are associated with falls after stroke: increased frequency of external assistance during testing, 'no-step' responses, decreased foot clearance and delayed time to initiate stepping responses (onset to unload and time to foot-off) were all associated with increased rates of falling within stroke inpatient rehabilitation (Mansfield et al. 2013). The inability to step with the non-preferred limb in response to instability (despite the preferred limb being physically blocked) has also been found to be predictive of falls after discharge from stroke rehabilitation and return to the community (Mansfield et al. 2015c). This would suggest that the assessment of reactive balance control after stroke, specifically reactive stepping, is worthy of clinical focus.

1.7 Training reactive stepping to reduce fall risk

Traditional exercise and balance training interventions have not been found to be effective at reducing falls after stroke (Batchelor et al. 2010; Batchelor et al. 2012). Task-specific 'perturbation-based' balance training is an emerging and promising approach to training reactive balance responses necessary to prevent falls (Grabiner et al. 2014). Such training repeatedly exposes the individual to an internally- or externally-generated balance perturbation, to induce instability, and evoke rapid reactive stepping responses. Methodologies have varied, incorporating water-based perturbations (Elbar et al. 2013), treadmill-delivered perturbations (Protas et al. 2005; Rosenblatt et al. 2013; Shimada et al. 2004), moveable platforms (Bhatt et al. 2012; Maki et al. 2008; Mansfield et al. 2010), cable pulls (Rogers et al. 2003), lean-and-release from a cable (Mansfield et al. 2011) and 'push' and 'pulls' by the supervising therapists (Marigold et al. 2005; Shen and Mak 2015; Smania et al. 2008). The intensity of training has varied from a single session of 24 perturbations (Bhatt et al. 2012) to 24 sessions with more than 800 perturbations (Protas et al. 2005). However, collectively studies have demonstrated that perturbation-based training can improve voluntary stepping time (Elbar et al. 2013; Rogers et al. 2003), speed and control of reactive stepping performance (Maki et al. 2008; Mansfield et al. 2010; Parijat and Lockhart 2012; Shen and Mak 2015) and 'in-lab' falls (Bhatt et al. 2012; Parijat and Lockhart 2012). Importantly, a systematic review has concluded that perturbation-based training can reduce real-life falls among older adults and those with Parkinson's disease [Mansfield 2015]. Research specific to the stroke population is limited. A group of community-dwelling older adults with stroke, who engaged in an agility exercise program including standing perturbation tasks, demonstrated faster voluntary step times, faster paretic rectus femoris muscle onset latencies and fewer 'in-lab' falls than those who engaged in stretching/weight-shifting exercises (Marigold et al. 2005). Over the course of 6 perturbation training sessions, an individual with sub-acute stroke decreased the need for external assistance, improved postural symmetry, more frequently stepped with the paretic limb and executed faster reactive steps, specifically improving speed within unloading and foot-off phases (Mansfield et al. 2011). Further research specific to stroke is warranted (Mansfield et al. 2015b). However, the collective results demonstrate that reactive stepping is modifiable and targeted training may result in reduced risk for falls. The implementation of

clinical assessments of reactive stepping that would inform such interventions is further underscored.

1.8 Balance assessment: current clinical practice

Balance assessment is a central feature of stroke rehabilitation to identify fall risk, inform treatment planning, evaluate effectiveness of interventions, and to ultimately optimize patient safety and independent mobility. The majority of physiotherapists agree that quantifying impairments and outcomes is important for patient care (Sibley et al. 2013) and a high proportion of therapists (90% of physiotherapists surveyed within Ontario, Canada) use at least one standardized balance measure within their practice (Sibley et al. 2011b). Indeed, there are an abundance of balance measures available for clinical use (Sibley et al. 2015) with numerous articles providing summaries of their respective psychometric properties, advantages and disadvantages for use in clinical practice (de Oliveira et al. 2008; Huxham et al. 2001; Mancini and Horak 2010; Pardasaney et al. 2013; Pollock et al. 2011). A recent survey identified more than 20 balance measures being used in current physical therapy practice (Sibley et al. 2011b). The Berg Balance Scale is the most commonly-used measure of balance (Blum and Korner-Bitensky 2008) and fall risk (Baetens et al. 2009) across the stroke rehabilitation continuum.

Of concern, reactive balance control is a component of balance least frequently assessed by Ontario physiotherapists (Sibley et al. 2011b). Limited availability of clinical tools to assess reactive balance control is among the top three cited barriers; this may seem surprising given the above-mentioned plethora of balance measures available. However, it may be

noteworthy that the most commonly-used balance measures do not provide information related to reactive balance control (Sibley et al. 2011b). The majority of therapists who do assess reactive balance control reportedly use a wide variety of non-standardized observationbased methods (Sibley et al. 2013); the lack of standardized administration and evaluation criteria is of obvious concern.

In actual fact, clinical assessments that probe reactive balance control, in response to a push or pull, do exist (Sibley et al. 2015). The therapist administering the assessment will typically nudge the individual (Ardolino et al. 2012; Di Fabio and Seay 1997; Tesio et al. 1997; Tinetti 1986), pull on their shoulders (Thomas et al. 2004; Visser et al. 2003), or the individual may lean or push against the therapist's hands, who then suddenly releases this support, to elicit a balance-recovery response (Horak et al. 2009; Rose et al. 2006). Although such tests are seemingly easy to apply within the clinical setting, there are challenges to implementation. Patient safety can be a real concern when inducing perturbations to balance-impaired individuals (Pak et al. 2015). There is no consensus on the most appropriate approach to induce a perturbation. Some perturbations are executed once (Franchignoni et al. 2010; Horak et al. 2009; MacKnight and Rockwood 1995; Padgett et al. 2012) whereas others are executed multiple times (Ardolino et al. 2012; Jacobs et al. 2006; Tinetti 1986; Wolfson et al. 1986). Some perturbations are expected, where the assessor provides the individual with prior warning, whereas others are unexpected (Visser et al. 2003). The perturbation forces imposed by the assessor when pushing or pulling can vary (Jacobs et al. 2006), making associated responses difficult to interpret. There is also no consensus on how the balance reaction should be scored. Many assessments are rated hierarchically, such that the use of FIP strategies receive a superior

score and responses that use a CIS stepping strategy are considered 'abnormal' responses to the balance perturbation (Ardolino et al. 2012; Di Fabio and Seay 1997; MacKnight and Rockwood 1995; Tesio et al. 1997; Thomas et al. 2004; Tinetti 1986; Wolfson et al. 1986). In recent years, clinical tests have emerged that specifically assess reactive stepping strategies, using a 'push-and-release' method (DePasquale and Toscano 2009; Franchignoni et al. 2010; Horak et al. 2009; Padgett et al. 2012; Rose et al. 2006). These assessments typically score performance on a 3-point (Franchignoni et al. 2010) or 4-point (Horak et al. 2009; Padgett et al. 2012) scale, based on the need for assistance or number of steps elicited to regain stability.

Observation-based measures of balance, however, may mask the mechanisms underlying performance (de Haart et al. 2004; Garland et al. 2007; Leroux et al. 2006). This may be particularly true in balance control when both the paretic and non-paretic limb contribute to task execution. The clinician can observe the behavioural outcomes of the tasks but must make hypotheses related to the source of dyscontrol. Perhaps most problematic in reactive balance control assessment are the temporal characteristics that cannot be noticed by a human observer. As previously mentioned, delays in early phases of stepping can influence the overall success or failure of the response (Lakhani et al. 2011a; Mansfield et al. 2011; Mansfield et al. 2013), are associated with falls in inpatient stroke rehabilitation settings (Mansfield et al. 2013) but occur prior to observable limb movement.

Methodologies and measurement technology that may better reveal such sources of dyscontrol are not part of routine clinical practice. Many techniques, for example translating platforms (McIlroy and Maki 1996a), are prohibitive for clinical use due to the cost, space and technological support required. Use of a weight-drop cable-pull has been proposed as a clinical

tool (Harburn et al. 1995), and a bidirectional cable system was piloted in stroke (Lakhani et al. 2011a), but limitations in its ability to deliver a brisk perturbation was suggested to influence responses and it was additionally considered too complex for routine application (Lakhani 2010). Alternatively, experimental paradigms using a lean-and-release methodology (Hsiao-Wecksler 2008) may be feasible. Specifically, the patient is attached to a safety harness and leans forward on a horizontal cable that is suddenly released, simulating a forward fall. The cable load associated with the lean angle can be easily measured, providing a means to control perturbation amplitude. Additional instrumentation (e.g. force plates) allows quantification of the response and qualitative performance can also be documented. When paired with a safety harness, this method may then allow for a safe, clinically feasible, standardized protocol for reactive stepping assessment.

1.9 Integrated knowledge translation

The setting for this research was purposeful; occurring within a novel patient care clinic that integrates both researchers and physiotherapists within a stroke rehabilitation setting (Inness et al. 2010a; Inness et al. 2010b). Healthcare professionals commonly cite a lack of 'reallife' relevance of research, and inability to generalize and apply findings to practice and the unique characteristics of individual patients (Salbach et al. 2007; Salbach et al. 2010). Research: clinical interaction is important to generate meaningful knowledge and enable clinical application of new innovations. In response, the clinic was developed to foster integrated knowledge translation (Graham and Tetroe 2007) and yield knowledge that is embedded within the clinical context and addresses the needs of the end-users. Clinic researchers and physiotherapists collaboratively developed a standardized balance and mobility assessment, integrating clinical and technological measures, that could be shared for both clinical and research purposes (Pak et al. 2015). The perturbation-evoked assessment of reactive stepping, using the lean-and-release methodology, was one component of a larger assessment that also included assessment of postural control in standing and gait. Ongoing feedback on utility guided the modification of the assessment protocol to align with clinical needs. The assessment evolved to become part of routine care for patients within inpatient stroke rehabilitation. The detailed and comprehensive assessments allowed for the development of a database, where data was collected prospectively but accessed retrospectively (as per the present studies), to generate new knowledge of balance control after stroke that related to the diverse and 'everyday' patient.

1.10 Summary

In summary, the risk of falls post-stroke is high with significant physical and psychosocial consequences. Fall rates rise dramatically within the weeks following discharge from the hospital. It is possible that current clinical balance assessments are not optimally identifying those at risk, or providing information to guide therapies during inpatient rehabilitation, to prepare individuals as they transition home to the challenges of daily life. A critical factor underlying falls is the ability to recover balance with a rapid, reactive step. Underlying temporal dyscontrol, specifically delays in early foot-off phases of reactive stepping, has been linked to falls after stroke. Of concern, reactive balance control is not routinely assessed within physical therapist practice, despite the availability of some clinical assessments. An alternate

experimental approach, the instrumented lean-and-release assessment, was developed for clinical use in a stroke rehabilitation setting as potentially feasible. One that could address limitations of safety, variability in administration, and provide an opportunity for precise quantification of characteristics of reactive stepping.

1.11 Research objectives

The primary objective of this dissertation was to advance understanding of reactive balance control, specifically reactive stepping, after stroke to inform and guide clinical assessment practices. The dissertation is comprised of three studies with three objectives: i) to identify the need for specific clinical assessments that target reactive balance control in early stages of recovery and rehabilitation; ii) to determine the potential for clinical uptake of a standardized reactive balance control assessment, using an instrumented lean-and-release methodology, within a stroke inpatient rehabilitation setting, and; iii) to identify underlying control issues, specifically the temporal characteristics of reactive stepping of both the paretic and nonparetic limb and their influence on balance-recovery performance, that may otherwise be masked in observation-based assessment methods.

The following chapters provide three separate studies designed to achieve the main objectives above. The dissertation concludes with considerations and recommendations for the future evolution of assessments of reactive balance control that are both effective and feasible for clinical uptake.

Chapter 2: Impaired reactive stepping among patients ready for discharge from inpatient stroke rehabilitation

Inness EL, Mansfield A, Lakhani B, Bayley M, McIlroy WE. Impaired reactive stepping among patients ready for discharge from inpatient stroke rehabilitation. *Physical Therapy.* 2014 94(12):1755-64

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2.1 Abstract

Background: Individuals with stroke are at increased risk for falls soon after hospital discharge. The ability to react to a balance perturbation, specifically with a rapid step, is critical to maintain balance and prevent falls. **Objective:** The purpose of the study was to determine the prevalence of impaired reactive stepping responses in an ambulatory group of patients with stroke who were preparing for discharge from inpatient rehabilitation and the relationship to patient performance on commonly-used clinical measures of balance, mobility, and lower limb impairment. **Design:** This study was a retrospective analysis of patient admissions over a 3-year period. Methods: Charts were reviewed for patients who, at time of discharge, had completed a perturbation-evoked reactive stepping assessment. **Results:** Ninety nine (71%) of 139 patients had impaired stepping reactions characterized by the need for assistance, an inability to step with either lower-limb, or the need for multiple step responses. There was a statistically significant difference in clinical scores between those with and without impaired stepping, but groups were characterized by considerable variation in clinical profiles. For example, Berg Balance scores ranged from 25 to 55 versus 20 to 56 and gait speeds ranged from 0.17–1.43 versus 0.26 to 1.55 m/sec for patients who demonstrated a failed step versus a successful step, respectively. **Limitations:** Not all patients who attended stroke rehabilitation received a reactive stepping assessment at discharge. **Conclusions:** Impaired reactive stepping is a prevalent problem for ambulatory patients with stroke preparing for discharge, possibly increasing their risk of falling when faced with the challenges of community ambulation. Specific tests

that target the capacity to perform perturbation-evoked stepping reactions may be important to identify those at risk for falls & to direct appropriate intervention strategies.

2.2 Introduction

The risk of falls for survivors of stroke is high (Forster and Young 1995; Weerdesteyn et al. 2008), with significant physical (Kanis et al. 2001) and psychosocial consequences (Andersson et al. 2008) that contribute to decreased independence, activity and participation (Schmid et al. 2012). Falls are common upon return to home after stroke. Fall rates as high as 73% have been reported (Forster and Young 1995) and the majority of falls occur within the first two months following discharge from rehabilitation (Mackintosh et al. 2005). It is possible, therefore, that we are not optimally identifying those at most risk, nor are we preparing these individuals during hospitalization for the challenges they will encounter in their everyday living environment (Weerdesteyn et al. 2008).

While challenges in the community may expose fall risk, the key factor that ultimately determines whether an individual will fall is their ability to recover from a loss of balance, specifically using a rapid stepping response (Maki and McIlroy 1997; Maki and McIlroy 2006). Reactive stepping responses are not only 'last resorts' to large-magnitude perturbations but also the preferred response to small-magnitude perturbations (Maki and McIlroy 2006) commonly observed in real-life situations (Holliday et al. 1990). Numerous age-related changes in reactive stepping responses have been observed. Elderly people are more likely to demonstrate a failed capacity to recover from instability than younger adults (Madigan and Lloyd 2005b; Wojcik et al. 1999) and more likely to take multiple steps

to restore balance (Luchies et al. 1994; McIlroy and Maki 1996a), a consequence of ongoing instability after the initial step (Maki and McIlroy 1999; Maki et al. 2001). Furthermore, such multi-step responses have been found to be predictive of falls in daily life among older adults (Hilliard et al. 2008; Maki et al. 2001).

Despite the importance of reactive stepping and despite the fact that early work by Harburn and colleagues (Harburn et al. 1995) proposed using a weight-drop cable-pull as a clinical method to test, there exists little research in this area with individuals with stroke. Findings from our previous pilot work suggest this is an important area of further study. Across patient cases, individuals in subacute stages of stroke demonstrate impaired anticipatory postural adjustments, delays in timing, an inability or unwillingness to initiate a step with the paretic limb, and the use of multi-step responses or the need for assistance to regain stability (Lakhani et al. 2011a; Mansfield et al. 2011). Importantly, features of reactive stepping have been associated with falls after stroke in inpatient rehabilitation (Mansfield et al. 2013) and, more recently, predictive of falls upon return to the community (Wong et al. 2013). Given the clinical attention directed toward balance and mobility re-training and falls prevention within rehabilitation, there is no doubt that greater insight into the magnitude of this clinical problem for patients with stroke is warranted.

Reactive balance control is less frequently assessed in clinical practice than other aspects of balance, possibly influenced by outcome measures that are most commonly used in clinical settings (Sibley et al. 2011b). A potential limitation of many clinical measures of balance, mobility or limb control is their focus on volitional limb control and

self-governed speed of movement that is fundamentally different than the control and speed required for reactive stepping (Luchies et al. 1999; McIlroy and Maki 1993b, 1996b). Therefore, it also is important to establish the association between patient performance on measures of reactive balance control and typical clinical balance, mobility, and limbimpairment measures.

Research conducted in the early phases of recovery is important to inform clinicians and guide interventions to potentially achieve important outcomes prior to discharge home. The present study affords a unique opportunity to examine reactive balance control performance in the early stages of stroke recovery with a focus on the point of discharge from inpatient rehabilitation to the community.

This study aimed: 1) to characterize the prevalence of residual impairment to reactive stepping among patients being discharged from inpatient stroke rehabilitation and; 2) to determine if commonly used clinical measures of balance (Berg Balance Scale [BBS]) (Berg et al. 1992; Berg et al. 1995), walking capacity (gait speed), and lower-limb impairment (Chedoke McMaster Stroke Assessment Impairment Inventory [CMSA]) (Gowland et al. 1993) could differentiate between patients with varying abilities of reactive balance control.

2.3 Method

This study was a retrospective chart review.

2.3.1 Setting and participants

The Balance, Mobility and Falls Clinic of the Toronto Rehabilitation Institute - UHN provides assessments of balance and gait using both technological and clinical measures as part of routine care. Assessments are administered at the discretion of the treating physiotherapist. All patients are considered for assessment but must be medically stable; have no musculoskeletal or other condition that could be exacerbated by the balance perturbation; have the cognitive-communicative ability to consent to the assessment, comprehend and follow instructions; and have the capacity to stand unsupported and walk at least 5 metres without physical assistance, with or without a gait aid,. Information was extracted from the clinic database (Mansfield et al. 2012; Mansfield et al. 2013) for patients assessed between October 2009 and September 2012. A total of 437 patients were discharged from stroke inpatient rehabilitation to the community during that time frame. From the 180 patients identified as having completed a discharge assessment of reactive stepping, 41 were excluded. Seventeen patients did not complete both test conditions (outlined below). Seventeen patients had participated in enhanced balance retraining. Three patients received nonstandardized instructions that could influence their responses. For 4 patients, there were technical difficulties that prevented observation and coding of video-recorded responses. Therefore, a final sample of 139 patients was included in subsequent analyses.

2.3.2 Protocol for reactive stepping assessment

Reactive stepping was evaluated using a "lean-and-release" balance perturbation method (Figure 2.1). Patients were instructed to lean forward from their ankles (and re-

instructed if improper form was used), and body weight was supported by a cable attached at chest height. At a varied and unexpected time, the cable was released, forcing patients to elicit a stepping reaction to regain stability (Hsiao-Wecksler 2008). Patients wore a safety harness attached to an overhead support, and a physical therapist provided supervision to ensure safety should balance recovery fail. The participants were assessed in their usual flat footwear and ankle-foot orthoses (if prescribed). Patients stood in a standardized foot position (heel centers 0.17m apart, 14° between the long axes of the feet (McIlroy and Maki 1997)) with one foot on each of 2 force plates [Advanced Medical Technology Inc., Watertown, MA]. Perturbations were delivered under 3 conditions and in the following order: 5 trials of unconstrained conditions, 1 trial of a dual-task condition, and 5 trials of encouraged-used conditions. The secondary task of the dual-task condition is nonstandardized; therefore, these data were not included in this study. Pre-perturbation cable load was monitored using a load cell [A-Tech Instruments Ltd, Scarborough, ON, Canada] mounted in series with the cable. Tension on the load cell is achieved through forward leaning, and cable load was used to determine the magnitude of the perturbation (Lakhani et al. 2011b; Ochi et al. 2013). The load on the cable was expressed as a percentage of body weight averaged over 1 second prior to the perturbation. There was no significant difference in patient cable load between the unconstrained and encouraged-use conditions (p=0.82); therefore, cable load values represent the average of the 2 conditions. Mean cable load across patients was 8.5% body weight (SD = 2.9%). A lean of 11% body weight corresponds to a whole-body lean angle of approximately 9° from vertical; this perturbation is of sufficient magnitude to consistently elicit a stepping response in healthy young adults with no balance impairment (Lakhani et al. 2011b). In unconstrained conditions, participants were

instructed to respond however they would naturally to recover balance. In encouraged-used conditions, the preferred stepping limb (the limb used most frequently in unconstrained conditions) was blocked to force stepping with the opposite limb. A physical therapist placed his or her hand approximately 5cm in front of the patient's shin. Participants were instructed to respond however you would naturally to recover balance knowing the preferred stepping limb was blocked. All tests were video-recorded and reviewed to code responses.



Figure 2.1. The 'lean-and-release' balance perturbation method. The patients wear a safety harness that is attached to an overhead support structure and leans forward on a cable connected to the support frame. The cable is released unexpectedly inducing a forward fall.

2.3.3 Measures

Features of reactive stepping extracted from the database were: level of independence following the perturbation (i.e. no assistance versus reliance on the harness or physical therapist to prevent a fall), multi-step responses (≥ 3 steps), and limb used for the initial step. Previous research linking multi-stepping with falls in the elderly have defined multi-step responses as responses involving more than 1 step (Hilliard et al. 2008; Maki et al. 2001). Given that it may be a natural response in a forward lean to use a follow-up second step to reestablish stability and base of support, we used a more conservative definition of multi-step responses as responses involving 3 or more steps. We examined only the first trial response of both the unconstrained and encouraged-use conditions because this test situation is most similar to that adopted in clinical settings (Horak et al. 2009; Tinetti 1986) and may have better ecological validity, representing the unpracticed response triggered by a fall in everyday life (Barrett et al. 2012; McIlroy and Maki 1995). Pre-perturbation limb load was calculated as the percentage of body weight borne under each limb, as measured by the force plates.

The specific clinical measures extracted from the database were: measures of functional balance (BBS) (Berg et al. 1992; Berg et al. 1995), walking capacity (gait speed), and lower-limb impairment (CMSA Impairment Inventory) (Gowland et al. 1993). Preferred gait speed was measured using a pressure-sensitive mat [GAITRite, CIR Systems Inc., Clifton, NJ] (Bilney et al. 2003; Wong et al. 2014). Participants walked over the 4.6 metre mat 3 times, wearing regular footwear. If the participant was tested with and without a walking aid, the average gait speed was chosen from the condition that yielded the fastest pace.

Participant characteristics extracted from the database included sex, age, affected hemisphere, time since onset, inpatient rehabilitation length of stay, functional mobility status (items of the Clinical Outcome Variables Scale denoting walking independence, use of aids and endurance) (Seaby and Torrance 1989), and patient balance self-efficacy (Activities-specific Balance Confidence scale [ABC]) (Powell and Myers 1995). The ABC was administered verbally only to those who had sufficient cognitive and communicative ability or English language comprehension to complete the questionnaire.

2.3.4 Data Analysis

All statistical analyses were performed with SAS 9.3 (SAS Institute Inc, Cary, North Carolina). Descriptive statistics were used to characterize the patient sample. Frequency values were used to describe the prevalence of patient trials exhibiting impaired stepping features. Based on their exhibited stepping reactions, patients were categorized into three groups: 1) failed step group: participants who demonstrated a failed capacity to step either by requiring assistance in unconstrained or encouraged-use conditions or attempting to step with the blocked limb during encouraged-used conditions; 2) multi-step group: participants who did not require assistance but who required multiple steps to regain stability; and 3) successful step group: participants who recovered balance in both conditions with 2 or fewer steps and without assistance.

A one-way analysis of variance was conducted to determine mean differences between groups on clinical measures; the Tukey test was used for pair-wise comparisons. The exact McNemar test was used to detect differences in the frequency of impaired stepping reactions

(failed or multi-step responses) between unconstrained or encouraged-used conditions. Paired *t* tests were used to determine differences in cable load between unconstrained or encouraged-used conditions. The Fisher exact test was used to detect proportional differences in impaired stepping reactions between those who initiated a step with their affected versus unaffected lower-limbs. For all statistical analyses, α =0.05.

2.4 Results

2.4.1 Participants

At discharge, participants were at a high functional-mobility level. Mean walking speed was 0.81 m/s (SD =0.32m/s). Eighty-nine percent (n=124) of the participants were able to walk independently on indoor surfaces (with/without a mobility aid or ankle-foot orthosis. Approximately half of the patient group (n=73) could walk distances of greater than 500m (see Table 2.1 for full clinical profile). As described above the entire cohort was sub-divided into 3 groups based on reactive stepping ability. There were no statistically significant differences between groups in age ($F_{(2,136)} = 1.47$, p=0.23), time since onset of stroke ($F_{(2,136)} = 1.85$, p=0.16), inpatient rehabilitation length of stay ($F_{(2,136)} = 2.72$, p=0.07), or balance self-efficacy ($F_{(2,100)} = 2.01$, p=0.14) for those with the cognitive-communicative ability to complete this questionnaire. In addition, there were no statistically significant differences between groups in the pre-perturbation limb load ($F_{(2,135)} = 2.13$, p=0.12) or in the amplitude of perturbation applied to the individuals as measured by the pre-perturbation cable load ($F_{(2,135)} = 0.03$, p=0.97).

Variable	All (N=139)	Failed step (n=59)	Multi-step (n=40)	Successful step (n=40)
Age (y)	66.0 (14.2)	67.9 (14.8)	66.1 (13.4)	62.9 (14.0)
Gender (men:women)	88:51	32:27	29:11	27:13
Inpatient rehab LOS (d)	33.2 (12.6)	35.5 (13.9)	33.4 (11.8)	29.6 (10.4)
Time post-stroke (d)	46.1 (18.8)	46.1(15.7)	50.0 (24.3)	42.0 (16.3)
Affected side (left:right:both)	54:72:15	20:31:8	19:18: 3 (n=40)	15:23:2
Functional Mobility Independence				
(Out: In: Sup'd) <i>Aid (</i> None: SPC: QC/W)	46:78:15 60:35:44	11:35:13 16:15:28	14:26:0 19:12:9	21:17:2 25:8:7
<i>Endurance</i> (>500m:<500m:<100m)	73:56:10	24:28:7	26:11:3	23:17:0
BBS (out of 56)	48.4 (7.3) (n=137)	44.8 (7.7) (n=58)	50.7 (4.4) (n=39)	51.4 (6.8) (n=40)
Walking velocity (m/s)	0.81 (0.32) (n=138)	0.70 (0.31)	0.82 (0.25) (n=39)	0.98 (0.33)
CMSA (out of 7) Leg Foot	(n=131) 5.1 (1.0) 4.6 (1.2)	(n=56) 4.7 (1.1) 4.1 (1.3)	(n=37) 5.3 (0.8) 4.7 (1.2)	(n=38) 5.6 (0.8) 5.3 (0.9)
ABC (out of 100)	71.5 (18.1) (n=103)	67.7(18.1) (n=39)	71.6(15.3) (n=33)	76.3(20.1) (n=31)
Cable Load (% total body weight)	8.5 (2.9)	8.6 (3.2)	8.4 (2.4)	8.4 (2.8)
Step Limb Load (% total body weight)	45.7 (8.1)	44.0 (10.5)	46.9 (6.3)	46.9 (4.6)

Table 2.1. Clinical profile of patients by category of reactive stepping ability.

N=139 unless otherwise specified. Values represent means (SD) or counts. Functional mobility status was determined from the Clinical Outcome Variables Scale. LOS=length of stay. Out:In:Sup'd= walking independently outdoors, independently indoors only, or requires supervision, respectively. SPC=single-point cane. QC/W=quad cane/ walker. BBS=Berg Balance Scale. CMSA=Chedoke McMaster Stroke Assessment Impairment Inventory. ABC=Activities-specific Balance Confidence Scale. Step Limb Load= pre-perturbation percentage of body weight under the limb used in the initial step.
2.4.2 Prevalence of impaired stepping responses

The frequency of participants exhibiting a failed, multi-step or successful stepping reaction across both unconstrained and encouraged-use conditions is displayed in Table 2.2. At time of discharge, only 40 out of 139 participants (29%) were able to exhibit a successful step in both unconstrained and encouraged-use conditions (successful step group) or, conversely 99 out of 139 participants (71%) had impaired stepping reactions. In terms of patient performance across both the unconstrained and encouraged-use conditions, 59 out of 139 participants (42%) exhibited a failed step (failed step group) and 40 out of 139 participants (29%) exhibited a multi-step reaction to regain stability (multi-step group).

The frequency of failed steps and multi-step reactions did not differ between unconstrained and encouraged-use conditions (p=0.74 and p=0.32, respectively). In unconstrained conditions, 62 out of 126 participants (49%) initiated a step with their affected lower limb (13 participants with bilateral or unspecified impairments were not included in this statistic). The frequency of failed or multi-step reactions was not significantly different for participants who initiated a step with their affected versus unaffected limb (p=0.44 and p=0.31, respectively). In encouraged-use conditions, 30 out of 139 participants (22%) attempted to initiate a step with the blocked limb; 15 out of 30 patients had their unaffected limb blocked.

Post-hoc analysis revealed that participants who initiated a step with their paretic limb in the unconstrained conditions bore significantly less weight (p=0.036) under their stepping limb (mean paretic stepping limb load 43.4% of total body weight [SD=9.1%]) than those who initiated a step with their non-paretic limb (non-paretic stepping limb load 47.3% of total body weight [SD= 11.5%]. There was no significant difference in CMSA leg scores between paretic and nonparetic steppers (5.1 [SD= 1.0] and 5.0 [SD=1.1], respectively; p=0.40). Chedoke-McMaster Stroke Assessment foot scores tended to be higher in paretic steppers (4.8 [SD=1.3]) than non-paretic steppers (4.4 [SD=1.3]); this difference approached statistical significance (p=0.08).

Table 2.2 Frequency of participants (N=139) who exhibited impaired reactive steppingperformance across unconstrained and encouraged-use conditions.

		Encouraged-Use Response					
		Failed step (Assist or Step with Blocked Limb)	Multi-step (No assist, ≥ 3 steps)	Successful step (No assist, ≤ 2 steps)	TOTAL		
Unconstrained Response	Failed Step (Assist)	24 (17.3)	7 (5.0)	9 (6.5)	40 (28.8)		
	Multi-step (No assist , ≥ 3 steps)	7 (5.0)	17 (12.2)	15 (10.8)	39 (28.1)		
	Successful step (No assist, ≤ 2 steps)	12 (8.6)	8 (5.8)	40 (28.8)	60 (43.2)		
	TOTAL	43 (31.0)	32 (23.0)	64 (46.0)	139 (100)		

Values represent number (%) of patients. Bold outlines demarcate patients who demonstrated a failed step or multi-step in either unconstrained or encouraged-use conditions and participants who demonstrated a successful step in both conditions; these participants represent those categorized in the Failed step (n=59 [42%]), Multi-step (n=40 [29%]), and Successful step (n=40 [29%]) subgroups.

2.4.3 Relationship to clinical measures

There were significant differences in BBS scores ($F_{2,134}$ =14.67, p<0.0001), walking velocity ($F_{2,135}$ =10.33; p<0.0001), and CMSA leg ($F_{2,128}$ =10.32; p < 0.0001) and foot ($F_{2,128}$ =11.62; *p*<0.0001) scores across patient groups. Pair-wise comparisons revealed significant differences (p<0.05) between those in the failed step and successful step groups for BBS (mean difference=6.6 /56; 95% confidence interval [95%CI]=3.3, 9.8), walking velocity (mean difference=0.28 m/s; 95% CI =0.13, 0.43) and CMSA leg (mean difference=0.9 out of 7; 95% CI =0.4, 1.4) and foot (mean difference=1.2 out of 7; 95% CI =0.6, 1.7) scores. Significant differences also were evident between those in the failed step and multi-step groups for BBS (mean difference=5.8 out of 56; 95% CI =2.6, 9.1), and CMSA leg scores (mean difference=0.6 out of 7; 95% CI =0.1, 1.0). Significant differences between those in the multi-step group and successful step groups were evident for mean walking velocity (mean difference=0.16m/s; 95% CI =0.003, 0.33). Despite these significant statistical differences between groups, there were a wide range of clinical scores across groups of participants with varying levels of ability (Figure 2). For example, participants in the failed step group demonstrated BBS scores ranging from 25 to 55 out of 56, walking velocity values from 0.17 to 1.43 m/s and both CMSA leg and foot scores from 2 to 7 and 2 to 6 (both out of 7), respectively.



Figure 2.2. Scatterplot of individual participant (A) Berg Balance Scale (BBS) scores and (B) walking speed values by sub-group of reactive stepping ability. Bars represent mean clinical scores within each subgroup. Asterisks represent significant group mean differences.

2.5 Discussion

To our knowledge, this is the first study to examine the prevalence of impaired reactive stepping in a large cohort of patients with stroke. The results of this study confirm our early pilot work (Lakhani et al. 2011a) and demonstrate that, despite having attained a high level of functional mobility, the majority of ambulatory patients discharged from inpatient rehabilitation are unable to successfully use reactive stepping to recover balance following an induced forward fall. Indeed, 71% of patients demonstrated the need for assistance, a failed capacity to evoke a step freely with either limb, or the need for multi-step reactions to regain stability. Such balance control issues could put these individuals at significant falls risk when faced with the daily challenges of community mobility and, therefore, are worthy of more focused clinical attention.

In contrast to earlier studies (Lakhani et al. 2011a; Mansfield et al. 2012), this group did not demonstrate a preference to use the non-paretic limb for the initial step. This could be attributed to methodological differences. Our previous study exploring determinants of limb preference measured paretic and non-paretic limb use across multiple step trials (Mansfield et al. 2012), whereas this study considered only the first, most novel step. However, in support of earlier study observations (Mansfield et al. 2012), results obtained from this larger cohort similarly showed that patients who initiated a step with their paretic lower limb tended to have better distal, lower limb motor recovery (higher motor CMSA foot, but not leg, scores) and bear less weight on their paretic limb prior to perturbation than those who stepped with their nonparetic limb. The latter finding could be due to an unwillingness or inability to load the paretic

limb; however, given the higher motor recovery scores of this sub-group, the latter finding may reflect a compensatory strategy to facilitate the necessary rapid response.

It is noteworthy, however, that patients were profoundly and equally challenged when stepping in both unconstrained and encouraged-used conditions and when initiating a step with the affected and unaffected limb. This finding may reflect the unique challenges of those with stroke; difficulties in speed and precision of lower limb control may limit the patient's ability to step with the affected limb, whereas challenges in loading the affected limb may limit the patient's ability to successfully execute a step with the unaffected limb. It may also be important to differentiate between the capacity to *initiate* a step and the capacity to execute a step of appropriate length, time and precision to successfully regain stability. Future research is warranted in order to better understand the spatiotemporal characteristics and underlying control issues of reactive stepping that may differentially influence the success or failure when stepping with the affected and unaffected limbs.

When patients were placed in conditions that constrained use of their preferred stepping limb, irrespective of whether it was the affected or unaffected limb, 22% of the participants initiated a step with their preferred, but blocked, stepping limb. The failure to freely evoke a balance reaction with either limb could put these individuals at obvious falls risk. The current study is limited to anterior perturbations where the selection of either limb in unconstrained conditions is a possible solution to the balance control challenge. However, when faced with unpredictable, multi-directional, balance perturbations of daily life, the need to be able to step with either limb is essential. This finding reinforces the need to assess (and train) stepping reactions of both the nonparetic and paretic limbs and supports the use of

encouraged-use paradigms of reactive stepping to provide valuable and additional clinical insights to patient performance.

The BBS is the most commonly used clinical measure in stroke rehabilitation for balance (Blum and Korner-Bitensky 2008) and fall risk (Baetens et al. 2009). Gait speed also often is used clinically as an overall measure of walking capacity and preparedness for safe community mobility (Lerner-Frankiel et al. 1986; Perry et al. 1995). Arguably, safe community mobility also encompasses the ability to successfully respond to the countless perturbations to balance (e.g. sudden stops, turns, bumps, slips, and trips) that occur in daily activities. It is noteworthy that neither of these measures could clearly discriminate between patients who, despite being poised for discharge to the community, had impaired stepping reactions that could put them at risk in this environment. The wide range of clinical scores for those with failed stepping reactions when balance was perturbed suggests that there are challenges in using these measures to predict performance at the level of the individual patient. Clinical measures that assess balance and mobility through voluntary movement may not appropriately challenge the individual with the timing or stability requirements necessary for successful perturbationevoked balance responses; they may provide misleading information about patients' balance abilities in these situations.

A strength of this study was its ability to characterize performance in the "typical" patient. This characterization was made possible by the implementation of a lean-and-release methodology in routine clinical practice, a safe, standardized protocol to measure capacity for reactive stepping within the sub-acute stages of stroke. Not all patients admitted to inpatient rehabilitation, however, received a discharge assessment. Patients who do not receive this

reactive balance control assessment tend to be at lower levels of functional mobility with greater lower limb impairment than those assessed (E.L. Inness; unpublished data, 2014). It is possible, therefore, that the prevalence of impaired reactive stepping would be greater than the present results suggest if all patients were included in the present study. However, given that the majority of patients after stroke regain the capacity to walk (Jorgensen et al. 1995) and walking is the most common activity in which falls occur upon discharge to the community (Weerdesteyn et al. 2008), we believe the present sample is representative of, and provides insights into the magnitude of reactive balance control impairment within, the ambulatory patient with stroke poised for discharge. The lean-and-release method is limited to a forward fall; it is not intended to mimic all possible "real-world" falls that may occur in various directions or environmental conditions. It is, however, intended to reveal the patient's capacity to respond with a reactive step to challenging and temporally unpredictable perturbations to balance. Through use of this method, it has been determined that reactive stepping is associated with falls after stroke in inpatient rehabilitation (Mansfield et al. 2013) and is predictive of falls upon return to the community (Wong et al. 2013). These previous studies provide support for the validity of the lean-and-release test and the relevance of the present findings to potential fall risk for the patient with stroke returning to the community.

Future research should explore the feasibility of implementing more specific and standardized assessments of reactive balance control into clinical practice. There were no differences in cable load between groups; however, there was notable variation in cable load among individuals. This contrast suggests that either patients had varying abilities or comfort level in leaning forward or therapists were preselecting perturbation amplitudes relative to the

functional ability of the individual patient. Attention to maintaining comparable perturbation amplitude across assessments would be important for evaluation of change within individual patients. Standardizing criteria for choice of perturbation amplitude across varying patient abilities also would be important for the ongoing development of these methods for use in clinical practice. Alternative methods of perturbation could be explored. Further understanding of the most appropriate and clinically meaningful measures would also be important. The present study restricted its analyses to observational measures. However, important features that cannot be detected through observation (e.g. time required for step initiation) can influence the overall success or failure of the stepping response (Lakhani et al. 2011a; Mansfield et al. 2011; Mansfield et al. 2013), suggesting that there is potential added clinical value of pairing technological measures with this methodology. Future research using kinetic, and electromyographic analysis are warranted to gain insight into the underlying control issues of reactive stepping after stroke. The relationship between reactive balance control and other measures beyond fall risk, including functional mobility status, balance confidence, physical activity and participation, should be explored, allowing for the evolution of clinically meaningful measures to ultimately guide more focused treatment.

In conclusion, impaired balance-recovery stepping reactions are a prevalent problem among ambulatory stroke patients preparing for discharge. Impaired balance-recovery stepping reactions may increase risk of falls for members of this population when faced with the challenges in the community. This aspect of balance assessment, therefore, is worthy of more focused clinical attention. Specific tests that target the capacity to perform reactive stepping

may be important to identify those at risk for falls and to direct appropriate intervention strategies.

Chapter 3: Clinical implementation of a reactive balance control assessment in a sub-acute stroke patient population using a 'lean-and-release' methodology.

Inness EL, Mansfield A, Lakhani B, Biasin L, Brunton K, Bayley M, McIlroy WE. Clinical implementation of a reactive balance control assessment in a sub-acute stroke patient population using a 'lean-and-release' methodology. *Gait & Posture*. 2015; 41: 529-534.

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3.1 Abstract

Reactive balance control, specifically performance of rapid stepping responses, is associated with falls, but not routinely assessed in clinical practice. Challenges to clinical assessment may include a lack of available methods that are safe, standardized and able to quantify the balance responses. We implemented a reactive balance control assessment, using lean-and-release methodology, in an inpatient stroke rehabilitation program. Through retrospective chart review of all admissions (n=183) over a 1-year period, we evaluated the clinical uptake and patient-specific factors associated with its use. Seventy seven of 183 (42%) patients were administered the assessment, on average, 16.2 (SD 13.1) days post-admission. Patients who received the assessment were younger, at an earlier time post-stroke, with a shorter rehabilitation length of stay, with less lower-limb impairment, higher levels of functional balance, less motor and cognitive impairment, greater recovery of functional mobility, and were more likely to have the capacity to walk (all measures p<0.0001), compared to those who did not receive the assessment. This study demonstrates the potential for clinical uptake of the lean-and-release assessment among patients with stroke, who are progressing in their functional and mobility status over the course of their inpatient rehabilitation. However, the results suggest limitations in application to patients with greater disability or who demonstrate slower recovery of functional mobility. Ongoing research is required to develop clinical approaches to reactive balance control assessment that are effective, efficient and relevant to clinical populations and feasible for clinical practice.

3.2 Introduction

Falls risk post-stroke is high with significant physical and psychosocial consequences contributing to decreased independence, activity and participation (Weerdesteyn et al. 2008). A critical factor underlying falls is the lack of ability to recover from a loss of balance, specifically using a rapid stepping response (Maki and McIlroy 2006). Reactive stepping performance is predictive of falls among community-living elderly (Hilliard et al. 2008; Maki et al. 2001), associated with falls among those with stroke in inpatient rehabilitation (Mansfield et al. 2013) and predictive of falls after discharge to the community (Wong et al. 2013).

However, reactive balance control is not routinely assessed in physiotherapy practice (Sibley et al. 2011b). Commonly-used clinical measures focus on volitional limb control and selfgoverned speed of movement (Sibley et al. 2013). Limited availability of clinical tools is among the top three cited barriers to improving assessment practices of reactive balance control (Sibley et al. 2013). Assessments that probe reactive balance control in response to a push or pull do exist (Horak et al. 2009; Tinetti 1986). Additional challenges to clinical implementation may include safety concerns (Harburn et al. 1993) and difficulties in using a standardized protocol with a controlled method of perturbation and quantification of response. Observation-based measures may also mask mechanisms underlying performance (Garland et al. 2003; van Asseldonk et al. 2006). For example, delays in step initiation phases, that occur prior to observable limb movement, can influence the overall success or failure of a response (Mansfield et al. 2011; Mansfield et al. 2013; Wong et al. 2013).

Many methodologies, for example translating platforms (Mansfield and Maki 2009), are prohibitive for clinical use due to the cost, space and technological support required. Use of a

weight-drop cable-pull has been proposed as a clinical tool (Harburn et al. 1993) and a bidirectional cable system was piloted in stroke (Lakhani et al. 2011a), but considered too complex for routine application. Alternatively, experimental paradigms using a lean-andrelease methodology (Hsiao-Wecksler 2008) may be feasible. Specifically, the patient is attached to a safety harness and leans forward on a horizontal cable that is suddenly released, simulating a forward fall. The cable load associated with the lean angle can be easily measured, providing a means to control perturbation magnitude. This approach (detailed below) was, therefore, developed as a standard technique in a stroke rehabilitation setting, to address the current gap in assessment practice of reactive balance control.

This study evaluated the clinical uptake of the lean-and-release methodology as a reactive balance control assessment for patients within inpatient stroke rehabilitation, specifically by determining: i) to what extent was the assessment used and implemented clinically, and; ii) what were the patient-specific determinants that influenced use of this assessment methodology?

3.3 Method

This study was a retrospective chart review approved by the institution's research ethics board.

3.3.1 Setting and Participants

Assessments were administered within a novel on-site clinic that partners researchers and clinicians, with an aim to accelerate new technology and findings into practice. An assessment,

that integrates technological (e.g. force plates, pressure-sensitive mats) and clinical measures to assess balance and gait, was collaboratively developed (Pak et al. 2015). The lean-andrelease assessment is one component of the larger assessment. The 'front-line' physiotherapists administer the assessment within the clinic as part of routine practice. Trained health-care students assist with equipment operation and post-processing of force plate data for the clinical report.

A retrospective review was conducted for consecutive admissions to the Stroke inpatient rehabilitation program over a 1-year period, specifically October 2011 to September 2012. From the 189 patients identified, 1 patient was excluded due to an extremely short length of stay (1 day) and 5 patients were excluded who were discharged to acute care, due to medical status change, and did not complete inpatient rehabilitation. A final sample of 183 patients was included in subsequent analyses.

3.3.2 Lean and Release Methodology

The lean-and-release balance perturbation assessment simulates a forward fall (see figure 3.1). A commercially-available, over-bed transfer gantry (Prism Medical, Concord ON, Canada) was modified to provide a low-cost harness system that allowed for unrestricted movements but ensured safety if the patient was unable to recover balance. The individual is held in a static forward lean position by means of a horizontal cable, attached at the level of his/her chest, which is released unexpectedly.



Figure 3.1. The 'lean-and-release' balance perturbation method. A 4-post overbed transfer gantry was modified: legs were elevated to accommodate standing beneath the frame and a cross-bar was added for cable attachment. The patient wears a safety harness that is attached to the overhead support structure. The patient leans forward on a cable connected horizontally to the frame. The cable load associated with the lean angle is measured to determine the magnitude of the perturbation. The cable is released unexpectedly inducing a forward fall. The assessment is video-recorded to document patient performance, including need for assistance, number of steps required and stepping limb preference. Force plates were added to provide measures of pre-perturbation symmetry (body weight beneath both feet) and timing of response. The force plate positioned in front captures foot contact time of the stepping limb.

Magnitude of perturbation: A standardized template for pre-perturbation standing position was adopted (McIlroy and Maki 1997). A load cell [A-Tech Instruments Ltd, Scarborough, ON, Canada] was mounted in series with the tether cable to measure pre-perturbation cable load (during the forward lean) and quantify the perturbation magnitude when the cable was released. Cable load was monitored by the physiotherapist across all trials. Patients were encouraged to lean forward from the ankles such that 8-10% of their body weight was consistently supported. For reference, 10-12% body weight corresponds to a whole-body lean angle of approximately 9° from vertical and is of sufficient magnitude to consistently elicit a stepping response in healthy young adults (Lakhani et al. 2011b). Lesser lean angles were allowed at the therapist's discretion, according to functional ability of the patient.

Measurement: The assessment was video-recorded to enable review of patient performance (e.g. need for assistance, stepping-limb preference, number of steps required) (Inness et al. 2014a). We additionally used force plates (Advanced Medical Technology Inc, Watertown, MA) to measure patients' stance symmetry (percent body weight under each lower limb) and timing of stepping responses (e.g. foot off, swing and foot contact time) referenced to the onset of perturbation (Mansfield et al. 2011; Mansfield et al. 2013).

Tasks and instructions: The assessment protocol included two task conditions: 5 trials each of preferred-response (PREF) and encouraged-used (ENC). In PREF, patients were instructed to 'respond however you would naturally to recover your balance'. In ENC, the preferred stepping limb (most frequently used in PREF) was blocked by the physiotherapist, by placing his/her

hand or foot approximately 5cm in front of the patient's shin, to encourage stepping with the opposite limb. The patient was instructed to 'respond however you would naturally to recover your balance, knowing that I have blocked this limb'.

This set-up was deemed to provide a safe, quantifiable and standardized method for measuring reactive balance control.

3.3.3 Measures

Patients were classified as to whether they received (REACT) or did not receive (NoREACT), the reactive balance control assessment. Patient characteristics extracted from health records included gender, age, height, weight, time post-stroke, affected side and length of stay (LOS). Patient clinical profile was determined from the following measures: Chedoke-McMaster Stroke Assessment Impairment Inventory (CMSA) (lower-limb impairment) (Gowland et al. 1993); Berg Balance Scale (BBS) (Berg et al. 1995), St. Thomas Risk Assessment Tool in Falling (STRATIFY) (Oliver et al. 1997), and history of falls during inpatient stay (functional balance and fall risk); Functional Independence Measure (Granger et al. 2009), total (FIM-T), motor (FIM-M) and cognitive (FIM-C) subscores (functional disability), and; Clinical Outcome Variables Scale (COVS) (Seaby and Torrance 1989) (functional mobility and walking status).

3.3.4 Data Analysis

Statistical analyses were performed with SAS 9.3 (SAS Institute, Inc, Cary, North Carolina, USA). Descriptive characteristics were used to characterize the patient sample. Frequency values were used to describe the prevalence of clinical use of the assessment and trials and conditions successfully completed. Unpaired t-tests and Fisher's Exact tests were used to detect mean and proportional differences in patient characteristics across REACT and NOREACT groups. A two-way analysis of variance was conducted with factors of group (REACT and NOREACT) and time (admission and discharge), to determine differences in clinical profile across patient groups. For all statistical analyses, α =0.05.

3.4 Results

3.4.1 Clinical Use & Implementation

Seventy seven of 183 (42%) stroke inpatient admissions were administered a lean-andrelease reactive balance control assessment during their rehabilitation stay. Of those assessed, 27/77 (35%) completed both initial and discharge assessments whereas 50/77 (65%) received only one assessment. On average, the first assessment occurred 16.2 (SD13.1) days postadmission; this equated to the midpoint (50.6% SD26%) of patients' overall LOS. Post-hoc analyses revealed that patients who received one assessment received this significantly later (p<0.0001) in their rehabilitation (20.0 SD 14.5 days; 61% SD25% LOS) than those who received both initial and discharge assessments (9.1 SD5.9 days; 30% SD14% LOS). There were no other differences (all comparisons p>0.25) in patient characteristics (gender, age, height, weight, time post-stroke, affected side, inpatient length of stay) or clinical profile during rehabilitation (CMSA leg/foot, BBS, fall risk score, history of falls, FIM-total/motor/cognitive, COVS, walking status) between those who received one versus two assessments.

Across patients, 98.5% (1065/1081 trials) of perturbations elicited a stepping response, with a mean cable load of 7.9% (SD3.0 %) body weight. Nine of the 16 trials that did not elicit a

step required support from the therapist and/or harness system for balance recovery (n=4 trials), elicited a grasp response where the patient reached to the therapist for support (n=1 trial) or both (n=4 trials). At initial assessment, 75/77 (97.4%) and 66/77 (85.7%) of REACT patients completed ≥3 of 5 trials of the PREF and ENC conditions, respectively. Eight of 77 (10.4%) patients did not complete any ENC trials: five patients exhibited failed responses in the preceding PREF trials (including trials with total assistance and no observable stepping reaction); two patients had difficulty understanding instructions, due to English as a second language; and one therapist administered additional PREF trials (where observably the patient used both their paretic and nonparetic limb).

3.4.2 Patient-specific determinants of reactive balance control assessment

Patient characteristics and clinical profile for REACT and NoREACT patients are found in Table 3.1. The distribution of individual patient scores on functional balance, disability and mobility measures, for NoREACT and REACT patients, is displayed in Figure 3.2. At time of admission, REACT patients were younger (p=0.002), earlier post-stroke (p=0.005) and had a shorter LOS (p=0.005) than NoREACT patients. There was a significant group by time interaction for COVS ($F_{(1,152)}$ =5.32;p=0.023); REACT patients made greater change in functional mobility than NoREACT during rehabilitation. Post-hoc analyses revealed significant betweengroup differences in COVS scores at time of admission (p=0.003) and discharge (p<0.0001). There were no other significant interaction effects. There was a main effect of time for all other clinical measures (all p<0.0001). There was a main effect of group: REACT patients had significantly less lower-limb impairment (CMSA leg/foot), higher functional balance scores

(BBS), less functional disability (FIM-T, FIM-M, FIM-C), and were more likely to be able to walk without assistance (all p<0.0001) compared to NoREACT patients. There were no differences in identified fall risk (STRATIFY) but REACT patients were less likely to experience a fall during rehabilitation than NoREACT patients (p=0.005). Post-hoc review revealed that 7 of 8 REACT and 24 of 29 NoREACT patients who fell, did so during wheelchair transfers while the remaining patients fell during upright stance or walking.

	REACT n=77		NoREACT n=106		Group comparison	
	Admission	Discharge	Admission	Discharge	<i>p</i> -value	
Patient characteristics						
Sex (male: female)	45:32	-	53:53	-	0.29	
Age (y)	63.9 SD 14.7	-	70.4 SD 12.8	-	0.002	
Height (cm)	167.4 SD 8.3	-	165.4 SD14.0	-	0.22	
Weight (kg)	73.0 SD 17.1	-	71.6 SD 14.6	-	0.59	
Time post-stroke (d)	14.1 SD 12.0	-	19.2 SD 15.0 (<i>n=103*</i>)	-	0.005	
Affected side (L:R:Both:No)	36:35:5:1	-	53:39:3:11	-	0.43	
Inpatient rehab LOS (d)	30.6 SD 15.8	-	39.7 SD 27.4	-	0.005	
Lower limb impairment						
CMSA - Leg (out of 7)	4.7 SD 1.7 (n=73)	5.1 SD 1.0 (n=57)	3.9 SD 1.3 (n=83)	4.2 SD 1.2 (n=63)	F _(1,158) =22.1;p<0.0001	
CMSA - Foot (out of 7)	4.3 SD 1.4 (n=73)	4.6 SD 1.3 (n=57)	3.3 SD 1.3 (n=82)	3.7 SD 1.5 (<i>n=62)</i>	F _(1,156) =21.4;p<0.0001	
Functional balance & fall risk						
BBS (out of 56)	35.4 SD 16.6	50.4 SD 5.1 (n=71)	22.8 SD 17.8 (n=104)	35.6 SD 14.6 (<i>n=89)</i>	F _(1,180) =43.8;p<0.0001	
STRATIFY 'high' fall risk	27/75 (36%)	-	51/104 (49%)	-	0.09	
In-patient fall history (≥ 1 fall)	-	8/77 (10%)	-	29/106 (27%)	0.005	
Functional disability						
FIM-T (out of 126)	86.7 SD 19.6 (n=72)	115.5 SD 7.7 (n=72)	73.0 SD 23.7 (<i>n=99</i>)	98.7 SD 19.9 (n=98)	F _(1,169) =31.6;p<0.0001	
FIM-M (out of 91)	60.5 SD 18.0 (n=72)	84.2 SD 6.1 (n=72)	50.3 SD 20.4 (<i>n=99</i>)	70.9 SD 16.5 (<i>n=98</i>)	F _(1,169) =25.6;p<0.0001	
FIM-C (out of 35)	26.2 SD 5.5 (n=72)	31.4 SD 3.8 (n=72)	22.7 SD 5.9 (n=99)	27.8 SD 5.2 (<i>n=98)</i>	F _(1,169) =21.9;p<0.0001	
Functional mobility					**	
COVS (out of 91)	63.8 SD 16.7	80.5 SD 6.6 (n=70)	55.8 SD 17.0 (n=102)	67.9 SD 13.3 (n=84)	<i>Ax:</i> F _(1,177) =9.3; p=0.003 <i>DC:</i> F _(1,152) =52.1; p<0.0001	
Walk without assist: yes (%)	46/77 (60%)	70/77 (91%)	40/106 (38%)	67/106 (63%)	F _(1,181) =26.9; p<0.0001	

Table 3.1. Clinical profile of patients who received a lean-and-release reactive balance control assessment (REACT) versus those who did not (NoREACT) during inpatient stroke rehabilitation.

REACT and NoREACT group are n=77 and n=106, respectively unless otherwise stated.

* n=3 outliers were removed from analysis where time post-stroke at admission ranged 159- 243 days.

L=left. R=right. LOS=length of stay. CMSA = Chedoke McMaster Stroke Assessment Impairment Inventory. BBS=Berg Balance Scale. STRATIFY=St. Thomas Risk Assessment Tool in Falling. FIM-T, FIM-M, FIM-C=Functional Independence Measures, total, motor and cognitive subscores, respectively. COVS=Clinical Outcome Variables Scale. Walk without assistance: extracted from COVS Item 5 'Performance of Ambulation' and included all patients who scored \geq 4 i.e. could walk with supervision or independently with/without walking aid.

**COVS analyses revealed group by time interaction therefore group comparisons were performed separately at admission (Ax) and discharge (DC). For reference, high scores on the CMSA, BBS, FIM and COVS mean less lower-limb impairment, greater functional balance abilities, less functional disability and greater functional mobility, respectively.



Figure 3.2. Distribution of scores for those who received the reactive balance control assessment (REACT n=77) versus those who did not (NoREACT n=106) on measures of functional balance (Berg Balance Scale-BBS), disability (Functional Independence Measure (FIM-T) and mobility (Clinical Outcomes Variables Scale – COVS). Data points represent individual patient scores; rectangles represent mean scores of measures at admission and discharge.

3.5 Discussion

This study aimed to determine the clinical uptake of a standardized lean-and-release assessment method adapted for use within an inpatient stroke rehabilitation program. The results suggest that the reactive balance control assessment was adopted for clinical use with a substantial proportion, although not majority, of patients. Clinical profiles suggest that most patients assessed had considerable post-stroke balance and mobility impairments. However, on average, patients more likely to be assessed versus not, were younger, at an earlier time poststroke, with shorter length of stay, less lower-limb impairment, higher levels of functional balance, less motor and cognitive disability, greater recovery of functional mobility, and more likely to have the capacity to walk without physical assistance. The assessment consistently elicited a reactive stepping response. The majority of patients were able to complete both preferred and encouraged-used trials. The results of this study demonstrate the potential for clinical uptake of reactive balance control assessment methodologies that may better reveal and quantify underlying dyscontrol. The clinical profiles of REACT patients suggests that, on average, physiotherapists are likely to administer this assessment as the patient progresses during the course of their inpatient rehabilitation. Plausibly, an evaluation of a patient's capacity to use a reactive step for balance recovery increases in importance as the patient gains independence in standing and walking. The majority of patients after stroke regain the capacity to walk (Jorgensen et al. 1995); however, walking is the most common activity preceding falls after discharge to the community (Weerdesteyn et al. 2008). It would be appropriate, then, for

physiotherapists to prioritize assessment of a patient's reactive balance control in the course of their rehabilitation and as they prepare for discharge from the hospital.

However, the results also suggest that there are limitations to the use of this assessment within early stages of post-stroke recovery that require further investigation. Differences in clinical profiles between REACT and NoREACT patients suggest there are perceived limitations to administering this more challenging balance assessment to those in early stages of rehabilitation who present with greater disability. Whereas the inability to stand would be an obvious and real barrier, further research is required to determine the factors that would limit application of this methodology to the lower-functioning individual who may benefit from the assessment. Some patients who were assessed also did not complete all trials and conditions; further investigation and modifications to the protocol may be warranted, to determine the optimal number of trials and conditions required to yield important clinical information.

The majority of patients (65%) were assessed approximately ten days before discharge which may limit the therapist in using the assessment to guide treatment at this late stage of rehabilitation. Effective methods to train reactive balance control (Mansfield et al. 2010; Mansfield et al. 2011) are emerging and there is encouraging evidence to suggest that rapid adaptations of balance control can occur post-stroke with only a few sessions of training (Mansfield et al. 2011). However, the necessary training dose that will translate to effective and learned responses when patients are exposed to real-life challenges is not yet known. A subgroup of REACT patients (35%) were administered the assessment earlier in their rehabilitation, allowing for therapeutic use of information gained and evaluation of interventions through

follow-up assessment. There were no obvious clinical differences to those who received one versus two assessments. Further research is therefore required to determine factors that may pose barriers to timely administration of the assessment.

Other patient-specific characteristics or comorbidities, not included in this study (e.g. unstable medical status, recent surgery, low exercise tolerance, musculoskeletal disorder or pain), may have influenced the choice to use the assessment or not, or timing of its implementation. Patient preferences or anxiety may have contributed to therapists' clinical decision-making (Pak et al. 2015). Alternatively, it is possible that the present results underestimate the potential clinical use: that many NoREACT patients were clinically appropriate for assessment, but other factors specific to the therapist or practice environment posed as barriers. Therapist time constraints have previously been cited as barriers to completing balance and gait assessments (Pak et al. 2015; Sibley et al. 2013). It may be noteworthy that, at time of discharge, the mean clinical scores of functional balance, disability and mobility for NoREACT patients were equal to, or surpassed, the REACT patients' admission scores. Plausibly, some NoREACT patients were clinically appropriate for assessment but were nearing their discharge from the hospital. It is possible, then, that considerations of both patient readiness for assessment juxtaposed with residual length of stay, influenced therapist decision-making. This is worthy of attention given current recommendations to accelerate the transfer of acute patients to inpatient rehabilitation, enabling earlier, intense therapy within a reduced length of stay (Meyer et al. 2012). Reactive stepping performance at time of discharge from stroke rehabilitation is predictive of falls upon return to the community (Wong et al. 2013). Further, fall rates are highest in the early stages after discharge from the hospital

(Weerdesteyn et al. 2008). The present results suggest that patients with slower rates of functional mobility recovery after stroke may not be adequately assessed (or trained). Given the importance of reactive balance control, we should continue to prioritize the development of effective yet also efficient clinical methodologies and processes that would support assessment and training of patients at this critical transition from rehabilitation to community living.

Interestingly, reactive balance control was not more likely to be assessed with patients who fell. It is possible that REACT patients received different treatment leading to fewer falls. However, the majority of falls occurred during wheelchair transfers, not during standing or walking. Such falls may be associated with circumstances where patients act against instructions or recommended supervision/aid (Weerdesteyn et al. 2008). The absence of an assessment for inpatient fallers may be more consistent with the NoREACT clinical profile of lower overall functional, motor and cognitive ability. However, given that a history of inpatient falls predicts future falls post-discharge (Mackintosh et al. 2006), the need to develop assessment approaches that are appropriate for those with slower rates of recovery is further underscored.

The collaboration between both clinicians and researchers, in developing and adapting the lean-and-release assessment for clinical care (Pak et al. 2015), most likely influenced its clinical uptake. Strong clinical:research partnerships can promote research utilization and foster best practices (Thomas and Law 2013). We recognize, however, that access to, and support for the administration of, the technology associated with this assessment would not be widely available in other clinical settings. However, it is important to differentiate between the

equipment required to implement the assessment methodology versus additional measurement technology used. A standardized methodology for assessing reactive balance control was implemented with relatively simple modifications to a transfer gantry, commercially available at a cost equivalent to that of other commonly-used therapeutic equipment (e.g. stationary bike). We added force plate measures, to gain information related to timing of responses, but meaningful clinical information can still be attained without this technology. Patient responses including need for assistance, decreased foot clearance and attempts to step with the blocked limb have been linked to falls post-stroke (Mansfield et al. 2013; Wong et al. 2013). Further, physiotherapists have advocated for the use of a harness system to safely incorporate reactive balance control assessment and training into practice, suggesting support for its clinical use. It is also noteworthy that inexpensive technological measures (e.g. game-based force plates, accelerometers) are being advanced (Mancini and Horak 2010), that can provide meaningful information in a more immediate and user-friendly format. Collectively, these factors bode well for the development of such methodologies and measures into clinically meaningful, accessible and feasible tools.

3.6 Conclusion

A standardized approach to reactive balance control assessment, using the lean-andrelease methodology with measurement technology, was developed for clinical use within a stroke inpatient rehabilitation setting. This assessment provides a safe and controlled method of balance perturbation. Added measurement technology allows for quantification of the patient's response that may reveal underlying balance control issues masked by observationbased methods. This study demonstrated the potential for clinical uptake of such assessment methods among patients with stroke, who were progressing in their functional and mobility status over the course of inpatient rehabilitation. However, patients with lower levels of cognitive and motor status and slower to progress with functional mobility, were not routinely assessed prior to discharge. Ongoing research is required to develop clinical approaches to reactive balance control assessment that are effective, efficient, relevant to clinical populations and feasible for clinical practice. Chapter 4: Reactive stepping after stroke: comparing paretic and nonparetic time to foot off.

Inness EL, Mansfield A, Bayley M, McIlroy WE. Reactive stepping after stroke: comparing paretic and nonparetic time to foot off. *JNPT;* September 2015 [Accepted].

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4.1 Abstract

Background and Purpose: Impaired features of reactive stepping, specifically delays in the early time to foot off (TFO) phase, are associated with increased fall rates after stroke. This study aimed to: determine differences in, and determinants of, paretic and nonparetic limb TFO, and; determine if both paretic and nonparetic TFO were associated with perturbation-evoked falls. Methods: Retrospective chart review of 105 individuals with stroke within an inpatient rehabilitation setting, who received a standardized assessment of reactive balance control at time of discharge. **Results:** There were no significant differences in paretic (351 ms) and nonparetic TFO (365 ms). The capacity to maximally load the nonparetic limb, the amplitude of the perturbation, and the capacity to load the paretic limb were all negatively associated with paretic step TFO, explaining 23.8% of the variance. The amplitude of the perturbation and the pre-perturbation load under the nonparetic stepping limb were, respectively, negatively and positively associated with nonparetic step TFO, explaining 22.7% of the variance. The likelihood of a perturbation-evoked fall was associated with mean nonparetic limb TFO but not paretic limb TFO. Discussion and Conclusions: Unique stroke-related impairments of dynamic balance control and limb-load asymmetry may differentially influence paretic and nonparetic reactive step TFO, in response to a loss of balance. The amplitude of the perturbation influences reactive step TFO in both limbs. The results of the present study have implications for the future development of standardized clinical assessment methodologies and training strategies to evaluate and remediate reactive stepping and reduce fall risk.

4.2 Introduction

It is well-established that individuals with stroke are at increased risk of falls (Weerdesteyn et al. 2008), with significant physical (Kanis et al. 2001) and psychosocial (Andersson et al. 2008) consequences that can contribute to decreased independence, activity and participation (Schmid et al. 2013). Fall rates are reported as high as 22% in acute care (Davenport et al. 1996), 47% within inpatient rehabilitation (Mayo et al. 1990), and up to 73% after discharge from hospital (Forster and Young 1995). While there are numerous factors that have been linked to falls, a critical factor is the ability to execute successful balance-recovery reactions in response to instability (Maki and McIlroy 1997). The focus of the current work is to explore the characteristics of balance-recovery reactions after stroke, in light of their important link to mobility and fall risk.

A critical response in recovering from loss of balance is the ability to take a rapid, reactive step (Maki and McIlroy 1997; Maki and McIlroy 2006). Despite the importance of reactive stepping and known link to falls in the elderly (Hilliard et al. 2008; Maki et al. 2001), research within the stroke population is only just emerging. It has been reported that 71% of ambulatory individuals with stroke have impaired reactive stepping performance at time of discharge from inpatient rehabilitation, not clearly identified by commonly-used clinical measures (Inness et al. 2014a). Impaired performance is characterized by the need for assistance, an inability to initiate a step freely with either the nonparetic or paretic limb, decreased foot clearance, multiple-step responses, or a lack of attempt to step (Inness et al. 2014a; Lakhani et al. 2011a; Mansfield et al. 2011; Mansfield et al. 2013). Importantly, recent studies have confirmed that features of reactive stepping performance are associated with falls after stroke in inpatient rehabilitation (Mansfield et al. 2013) and predictive of falls upon return to the community (Mansfield et al. 2015c). This would suggest that the assessment of reactive stepping after stroke is an important focus for clinical attention.

Of concern, reactive balance control is not routinely assessed within current clinical practice (Sibley et al. 2011b). In response, we implemented a standardized lean-and-release methodology as a measure of reactive balance control within an inpatient stroke rehabilitation setting, and demonstrated potential for clinical uptake (Inness et al. 2014b; Pak et al. 2015). Measurement technology (i.e. force plates) was added to reveal underlying balance control issues which can be masked by observation-based methods (Garland et al. 2003; van Asseldonk et al. 2006). The capacity to reveal the temporal characteristics of the response may be of particular importance. Markedly delayed stepping responses have been observed post-stroke (Lakhani et al. 2011a; Mansfield et al. 2011). Specifically, delays in early 'time to foot off' (TFO) phases, which occur prior to observable limb movement, are known to influence the overall success or failure of the response (Mansfield et al. 2011) and are associated with increased fall rates within inpatient rehabilitation (Mansfield et al. 2013). The potential to modify the temporal properties of reactive stepping, through task-specific, balance 'perturbation' training (Mansfield et al. 2011) has also been demonstrated. Collectively, this suggests that this early phase of reactive stepping may be important to both measure and target within clinical rehabilitation settings.

Surprisingly, we have little information about paretic limb timing within reactive stepping responses; only one pilot study has a reference to a paretic mean TFO value (Lakhani et al. 2011a). In this study, TFO was delayed moreso in trials where the individual with stroke

stepped with the paretic versus nonparetic limb (Lakhani et al. 2011a). Studies of perturbationevoked feet-in-place responses have also reported slower, more variable paretic limb muscle onset latencies (Badke and Duncan 1983; Di Fabio et al. 1986; Ikai et al. 2003) associated with paretic lower limb motor recovery (Badke and Duncan 1983). It is, therefore, plausible that paretic limb TFO would be delayed moreso than nonparetic limb TFO after stroke. However, unique stroke-related impairments may need to be considered. Individuals with stroke tend to bear more weight on their non-paretic limb (Eng and Chu 2002) and the capacity to load the paretic limb is less than the non-paretic when weight shifting (Bohannon and Larkin 1985); these impairments may differentially influence the time required to unload the nonparetic and paretic limb to initiate a reactive step.

The objectives of this study were, therefore, to: 1) determine if there were differences in reactive stepping TFO within the paretic versus nonparetic lower limb; 2) investigate the determinants of TFO within the paretic and nonparetic limb, and; 3) investigate the influence of TFO on the reactive stepping performance of those with stroke. We hypothesized that: i) paretic TFO would be delayed moreso than nonparetic TFO; ii) TFO would be negatively associated with paretic lower-limb motor recovery, positively associated with the load borne under the paretic or nonparetic stepping limb, and negatively associated with capacity to maximally load the paretic and nonparetic stance limbs during weight shift, and; iii) slower TFO would be associated with an increased likelihood of the individual to 'fall' in response to a postural perturbation.

4.3 Methods

Standardized assessment of reactive balance control is routinely conducted at the participating in-patient stroke institution. As a result, this study was able to be conducted as a retrospective chart review and was approved by the research ethics board of the Toronto Rehabilitation Institute – University Health Network.

4.3.1 Setting & Participants

Assessments were administered within an on-site clinic that integrates technological and clinical measures to assess balance and gait. The reactive balance control assessment (summarized below) is one component of the larger assessment and administered to individuals within stroke inpatient rehabilitation at the discretion of the front-line physiotherapists, as part of their routine practice. Individuals considered for assessment must be medically stable; have no musculoskeletal or other condition that could be exacerbated by the balance perturbation; have the cognitive-communicative ability to consent to the assessment, comprehend and follow instructions, and; have the capacity to stand unsupported and walk without physical assistance, with or without a gait aid, at least 5 metres. Information was extracted from the clinic database for individuals who completed a discharge assessment between October 2009 and September 2012. Of the 180 individuals who received a reactive balance control assessment at time of discharge, 75 were excluded: 23 did not have an identified paretic and nonparetic limb (i.e. bilateral impairments or 'no' affected side), 13 had musculoskeletal issues (e.g. previous hip or knee arthroplasty), 2 had concurrent neurological diagnoses other than stroke, 1 did not initiate any stepping responses during the assessment,

13 had targeted reactive balance control training during the course of their therapies, and 23 did not have trials for both paretic and nonparetic steps. Therefore, a final sample of 105 individuals with stroke was included in subsequent analyses.

4.3.2 Measures

Participant profile

Participant characteristics extracted from the database included age, sex, time poststroke, side of paresis, level of functional disability (Functional Independence Measure – total, motor & cognitive score) (Granger et al. 2009)and functional balance (Berg Balance scores) (Berg et al. 1995). Lower-limb sensory impairment was also extracted from physiotherapist assessments, as a binary variable (yes/no). These clinical sensory assessments were not standardized across therapists and, therefore, this data was not included as a predictor variable.

Response variable: Assessment of time to foot off during reactive stepping

Reactive stepping was evaluated using a 'lean-and-release' balance perturbation method. The lean-and-release assessment simulates a forward fall; the individual leans forward on a horizontal cable, attached at the level of his/her chest, which is released unpredictably in time, eliciting a reactive stepping response. In addition to physiotherapist supervision, the individual is attached to an overhead safety harness system to allow for unrestricted movements but safety should balance recovery fail. Participants are assessed under two conditions: up to 5 trials each of 'usual response' and 'encouraged-used'. In usual response
conditions, the individuals were instructed to 'respond however you would naturally to recover your balance'. In encouraged-use trials, the preferred stepping limb (the limb most frequently used in the usual response condition) was blocked by the therapist (placing their hand or foot approximately 5 cm in front of the shin), to force stepping with the opposite limb. Individuals were instructed to 'respond however you would naturally to recover your balance knowing that I have blocked this limb'. Individuals were assessed in usual, flat footwear and ankle-foot orthoses if prescribed. Individuals stood with one foot on each of two force plates [Advanced Medical Technology Inc., Watertown, MA] in a standardized foot position (heel centres 0.17m apart, 14cm between the long axes of the feet) (McIlroy and Maki 1997). A load cell placed in series with the horizontal cable measures the force placed on the cable when leaning, to ensure consistency of perturbation amplitude. Participants were encouraged to lean forward from the ankles such that 8-10% of their body weight was consistently supported. Previous research has determined that cable load values of this amplitude consistently elicit stepping responses among this patient cohort (Inness et al. 2014b). Lesser lean angles were allowed at the physiotherapist's discretion according to the patient ability or preference; however, trials with cable load of < 3% body weight were excluded from analyses. The load cell was also used to detect perturbation onset (i.e. time when force recorded was < 1N).

Time to foot off was measured as the time between perturbation onset and when the vertical force recorded under the stepping limb was <1% body weight. Load cell and force plate data were sampled at 256 Hz. The assessment was video-recorded and reviewed to confirm performance including the initial stepping limb (paretic or nonparetic) and occurrence of a perturbation-evoked 'fall' (i.e. need for assistance by the supervising therapist or harness).

Predictor variables

- i) Lower limb impairment was determined from the Chedoke-McMaster Stroke Assessment leg (CMSA-Leg) and foot (CMSA-Foot) stage of motor recovery scores (Gowland et al. 1993). The CMSA is a commonly-used clinical measure of motor impairment with established intrarater and inter-rater reliability and concurrent validity, when used with individuals within stroke rehabilitation (Gowland et al. 1993). The CMSA assigns a score between 1 and 7 with higher CMSA scores indicating greater motor recovery or less limb impairment.
- ii) Stepping limb load was determined by the percentage of total body weight (%BW) under the paretic/nonparetic stepping limb under two conditions: i) 'Usual stance', measured as the %BW on the limbs during quiet standing with eyes open, averaged over 30 seconds, and; 'Pre-perturbation', measured as the %BW on the limbs, averaged over 1 second immediately prior to the onset of the balance perturbation during the lean-and-release test.
- iii) The capacity to maximally load the paretic/nonparetic lower limb was determined by the %BW able to be borne under the respective limb, averaged over the duration of the trial. The individual stood on force plates, as outlined above, and was instructed to weight shift each to the paretic/nonparetic side and bear as much weight as possible on that limb, maintaining this position for up to 20 seconds.
- iv) Amplitude of the perturbation (cable load) was also included as a covariate of TFO, given that the magnitude of the perturbation could vary across individuals with varying functional abilities. Cable load was expressed as the %BW (averaged over 1 s prior to the perturbation) associated with the pre-perturbation lean angle.

4.3.3 Data Analysis

All statistical analyses were performed using SAS 9.2 (SAS Institute Inc, Cary, North Carolina). Descriptive statistics were used to characterize the sample. The mean values of TFO across trials were determined for the paretic and nonparetic limb of each individual with stroke, calculated with the first perturbation trial removed as it is known to have different characteristics than subsequent trials (Marigold and Patla 2002; McIlroy and Maki 1995). Encouraged-used trials, where the individual initiated a step with the blocked limb, were also excluded. Paired t-tests were used to determine differences in mean paretic versus nonparetic TFO within individuals (α = 0.05). Multivariate regression analyses were used to establish associations of predictor variables with nonparetic and paretic TFO. A stepwise method of regression analyses was then performed with variables entered in the model at a significance level of p≤0.15, to determine the most predictive variables explaining TFO. Correlational and variance inflation factor analyses were calculated to determine possible influence of multicollinearity. CMSA-Leg and CMSA-Foot scores were significantly correlated (r=0.63; p<0.0001) with variance inflation factors of 1.8 and 1.9, respectively. Regression analyses were repeated independently with significantly correlated variables removed. There was no impact on statistical inference with both or either CMSA-Leg/Foot scores included; therefore, the final model used only CMSA-Foot scores. Logistic regression was used to determine if paretic and nonparetic mean TFO was associated with increased likelihood for the individual with stroke to 'fall' during the assessment (i.e. need for physiotherapist or harness assistance within any trial).

4.4 Results

4.4.1 Participant profile

Participant profile is displayed in Table 4.1 for the 105 individuals with stroke who completed a reactive stepping assessment, at time of discharge from inpatient rehabilitation. Participant limb load values varied across quiet stance and pre-perturbation conditions. Mean paretic limb load was significantly greater during quiet stance (47.3 SD7.5 %BW) as compared to pre-perturbation (44.8 SD10.0 %BW) when stepping with the paretic limb (mean difference 2.5%BW; SD 9.7, 95%CI [0.6, 4.4]; *p*=0.009) and significantly less during quiet stance as compared to pre-perturbation (50.1 SD9.2 %BW) when stepping with the nonparetic limb (mean difference -2.8%BW; SD 9.3; 95%CI [-4.6, -0.9]; *p*=0.003). Pre-perturbation paretic limb load was also significantly less when stepping with the paretic limb versus the nonparetic limb (mean difference -5.3 %BW; SD 6.3; 95%CI [-6,-4]; *p*<0.0001)

4.4.2 Reactive TFO in the paretic and nonparetic lower limb

The participants' mean TFO values are displayed in Figure 4.1. There was no significant difference between mean paretic and nonparetic limb TFO (mean paretic 351 ms, mean nonparetic 365 ms; mean difference -14 ms; p=0.20).

4.4.3 Determinants of TFO in the paretic and nonparetic lower limb

Results of multivariate and stepwise regression analyses are displayed in Table 4.2. Within the final model, the capacity to maximally load the nonparetic limb, the amplitude of the perturbation (cable load) and the capacity to maximally load the paretic limb explained 23.8% of the variance in, and were all negatively associated with, paretic reactive step TFO ($F_{3,88}$ =9.18; *p*<0.0001). Within the final model, the amplitude of the perturbation (cable load) and the pre-perturbation load under the nonparetic stepping limb explained 22.7% of the variance in, and were respectively negatively and positively associated with, the nonparetic reactive step TFO ($F_{2,89}$ =37.52; *p*<0.0001).

4.4.4 TFO and consequences for perturbation-evoked falls

Sixteen of the 105 individuals (15%) fell during trials where they initiated stepping with the paretic limb; seven of 105 individuals (7%) fell during trials that initiated stepping with the nonparetic limb. The likelihood for the individual to fall was independently associated with nonparetic TFO (odds ratio = 1.009 [95% CI (1.003-1.015); p=0.003) but not paretic TFO (odds ratio = 1.006); p=0.95).

 Table 4.1. Characteristics of 105 individuals with stroke who completed a reactive stepping

assessment at time of discharge from inpatient rehabilitation.

Characteristic	
Age	63.5 SD 12.8
Sex (male:female)	69:36
Side of Stroke (R:L)	58:47
Time post-stroke (days)	43.2 SD 18.6
Functional Ability	
FIM-total out of 126*	114 SD 6.9
FIM-motor out of 91	83.1 SD 5.8
FIM-cognitive out of 35	30.9 SD 3.7
BBS out of 56**	49.7 SD 6.5
Sensorimotor impairment	
Lower limb sensory impairment (yes)	32 (30%)
CMSA Leg out of 7^{\dagger}	5.2 SD 1.0
CMSA Foot out of 7^+	4.7 SD 1.2
Asymmetry: Quiet Stance (%BW)	
Paretic limb load	47.3 SD 7.5
Nonparetic limb load	52.7 SD 7.5
Asymmetry – Pre-perturbation (%BW)	
Paretic step	
Paretic limb load	44.8 SD 10.0
Nonparetic limb load	55.2 SD 10.0
Nonparetic step	
Paretic limb load	50.1 SD 9.2
Nonparetic limb load	49.9 SD 9.2
Capacity to Load Limb (%BW)	
Paretic limb maximal load	78.7 SD 7.8
Nonparetic limb maximal load	82.5 SD 7.0
Amplitude of perturbation	
Cable Load (%BW)	9.5 SD 2.6

Values represent means and standard deviations (SD) for continuous variables and counts for categorical

variables. FIM= Functional Independence Measure (total, motor and cognitive subscores).

CMSA=Chedoke-McMaster Stroke Assessment Scale. BBS=Berg Balance Scale. BW=body weight.

Missing data for the following variables: *FIM n=102; **BBS n=101; **†**CMSA n=92.



Figure 4.1 Distribution of mean paretic and nonparetic limb time to foot off (TFO) values for 105 individuals with stroke who completed a reactive stepping assessment at time of discharge from inpatient rehabilitation. First trial values have been excluded. Boxes represent the interquartile range (IQR) of values (25-75th percentile). Solid line within box represents the median value. Diamond represents mean value. Whiskers represent 1.5 X IQR below the 25th percentile and above the 75% percentile. Circles represent outliers.

Table 4.2. Multivariate regression analyses to determine associations with paretic and nonparetic time to foot off (TFO) during reactive stepping assessment, for 105 individuals with stroke, at time of discharge from inpatient rehabilitation. Model 1 includes all predictor variables. Model 2 represents results of stepwise regression analyses with variables retained at significance level of $p \le 0.15$.

Model 1	Predictor Variables	F	R ²	Parameter Estimate	<i>p</i> -value
Paretic TFO	Model	4.89	0.257		0.0002
	CMSA-Foot			-1.9	0.81
	Usual stance paretic limb load			0.43	0.76
	Pre-pert paretic limb load			1.3	0.20
	Maxload:paretic limb			-2.4	0.08
	Maxload:nonparetic limb			-3.4	0.026
	Cable load			-8.1	0.026
Non	Model	4.27	0.232		0.0008
paretic TFO	CMSA-Foot			-4.6	0.60
	Maxload:paretic limb			0.71	0.64
	Maxload:nonparetic limb			0.17	0.92
	Usual stance nonparetic limb load			-0.32	0.84
	Pre-pert nonparetic limb load			2.7	0.019
	Cable load			-17.0	<0.0001
Model 2	Predictor Variables	F	R ²	Parameter	<i>p</i> -value
				Estimate	
Paretic TFO	Model	9.18	0.238		<0.0001
	Maximal load: nonparetic	15.67	0.148	-4.15	0.0002
	Cable load	8.06	0.071	-8.10	0.006
	Maximal load: paretic	2.24	0.019	-1.79	0.138
Non	Model	37.52	0.227		<0.0001
paretic TFO	Cable load	17.14	0.160	-16.42	<0.0001
	Pre-pert nonparetic limb load	7.67	0.067	2.75	0.007

CMSA-Foot = Chedoke-McMaster Stroke Assessment Scale stage of motor recovery for the paretic foot. Pre-pert = pre-perturbation

4.5 Discussion

This study revealed that, among those within sub-acute stages of stroke recovery, reactive TFO did not significantly differ when using the paretic versus nonparetic lower limb; however, the determinants of TFO did differ between limbs. Further, the likelihood of a perturbation-evoked fall was associated with TFO of the nonparetic, but not the paretic, limb.

This is the first study to compare paretic and nonparetic reactive TFO within individuals with stroke. In refute of our hypothesis, TFO was not slower in the paretic versus the nonparetic limb. In partial support of our hypotheses, the study results suggest that unique stroke-related impairments may differentially influence paretic and nonparetic reactive TFO. Greater capacity to weight shift and load the nonparetic limb (and, less so, to load the paretic limb) was associated with faster paretic TFO; this may suggest mediolateral dynamic stability contributes to paretic reactive step timing in early foot-off phases. Postural asymmetry resulting in greater load on the nonparetic lower limb, just prior to instability, was associated with slower nonparetic TFO. The above-mentioned factors may, therefore, be important to measure and target in interventions aimed at improving the temporal characteristics of the response. There is evidence to suggest that improvements in step timing, specifically TFO, can be achieved with task-specific 'perturbation-based' balance training (Mansfield et al. 2011). Ongoing research is focussed on determining the efficacy of such targeted, reactive balance control training after stroke (Mansfield 2015b).

There have been few studies to date examining reactive step TFO after stroke. TFO mean values reported within this study are somewhat faster than previous studies examining individuals within stroke inpatient rehabilitation. An initial pilot study (Lakhani et al. 2011a)

documented ranges between 515 and 891 ms, however, this study relied on a cable pull system for perturbations which may have led to slower initial accelerations and delays in timing of balance responses. A previous study, with a sub-group of the current cohort (Mansfield et al. 2013), documented mean values of 490 msec for fallers and 440 msec for non-fallers. The differences may be accounted for by differences in stage of rehabilitation/recovery (later in the current study) and the fact that the current study excluded the first trial. The present latencies are slower, however, than those previously reported for the healthy elderly using similar assessment methodology: the present mean paretic and nonparetic TFO values for stroke are at, or beyond, the upper confidence limits of values calculated from data reported by Thelen and colleagues (Thelen et al. 2000), in a cohort of healthy elderly (mean TFO 315 SD66 msec; 95%CI[273,357]; n=12). However, these elderly values were associated with greater lean angles (15% BW). Therefore, it is not clear if the delays in step initiation within the present study are a result of unique stroke-specific impairments or differences in perturbation amplitude. It is unlikely that our participants would have been able to achieve lean angles of this amplitude, given the profound challenge to balance recovery previously revealed at lesser lean angles (Inness 2014); direct comparisons, therefore, cannot be made.

Regardless of the differences between studies, rapid TFO latencies were evoked within the present paradigm for both the paretic and non-paretic limbs. It was most interesting that paretic limb timing was faster on average than the non-paretic limb. Two possible factors may account for such rapid paretic limb responses: 1) induced instability has the capacity to 'reflexively' evoke very rapid reactions (in spite of the slowing that may be evident when individuals are asked to move voluntarily) (Martinez et al. 2013), or; 2) the individuals may use

adaptive strategies (i.e. pre-loading the nonparetic limb in anticipation of a step with the paretic limb) to accomplish a more rapid time to unload the limb, despite poor motor control of the paretic in comparison to the nonparetic limb.

The lack of association, in this study, between clinical measures of lower-limb impairment and reactive step initiation suggests that commonly-used clinical measures did not clearly reveal impairments in reactive stepping performance. This finding supports the need to incorporate alternate methodologies and technological measures to better reveal and quantify underlying dyscontrol associated with reactive stepping performance.

It is noteworthy that limb load significantly differed when the individual was in 'usual stance' posture as compared to 'pre-perturbation' and, further, differed when the individual was stepping with the paretic versus nonparetic limb. As noted above, this could suggest that the individual was pre-planning and unloading the respective stepping limb to facilitate step initiation. The results also suggest that the amplitude of the perturbation can independently influence TFO within both lower limbs; larger amplitude results in faster responses. Collectively, this suggests that attention to both pre-perturbation limb load and cable load would be important for future standardization of methods and interpretation of the temporal characteristics of reactive stepping.

Previous study has demonstrated a positive association between TFO and falls within inpatient rehabilitation but did not differentiate between the paretic and nonparetic lower limbs (Mansfield et al. 2013). The results of the present study suggest that nonparetic, but not paretic, TFO may influence falls. Specifically, for every 1 ms increase in nonparetic mean TFO, there is a 1% increase in the odds of the individual with stroke falling in response to evoked

postural perturbations. Previous study has documented that individuals in sub-acute stages of stroke recovery commonly require multiple steps to regain stability (Inness et al. 2014a). It is plausible that if initiation of a paretic step was delayed, a follow-up step with the nonparetic limb may successfully recapture balance. In contrast, if initiation of a nonparetic step was delayed, the follow-up step with the paretic limb may not be able to successfully regain stability. This is speculative, but may highlight the importance of other features of paretic limb reactive stepping, such as step characteristics (length, time, placement) and the capacity to restabilize at step termination, that need to be considered within the context of reactive stepping and the link to falls.

The determinants of paretic and nonparetic reactive step TFO, as per the present regression analyses, explained less than 25% of the variance; we acknowledge the contribution of other factors, not included in this study, that may provide additional explanation of the variance in the regression models and require further study. It is recognized that TFO is a composite measure that can be further divided into step onset time, anticipatory postural adjustment time and stepping limb unloading time (Lakhani et al. 2011a). Future research should explore possible phase-specific delays of the paretic and nonparetic limbs, and their respective determinants, that may contribute to overall delays in TFO. The first trial was also excluded in the present analyses, for methodological reasons, but may be more ecologically valid than subsequent trials, representing the unpracticed response triggered by a fall in everyday life (Barrett et al. 2012; McIlroy and Maki 1995). The determinants and consequences of delays in step initiation revealed in this study may not generalize to this more novel stepping response. Future research should explore the temporal characteristics of the first trials and,

further, determine how best to incorporate this more novel response into standardized methods of measurement.

4.6 Conclusion

Unique stroke-related impairments of dynamic balance control and limb-load asymmetry may differentially influence reactive step time to foot off of the paretic and nonparetic lower limbs, respectively, in response to a balance perturbation. The amplitude of the perturbation influences reactive step time to foot off within both limbs. Delays in nonparetic, but not paretic, time to foot off increase the likelihood of the individual with stroke to fall. The results of the present study may have implications for the future development of standardized clinical assessment methodologies and training strategies to evaluate and remediate reactive stepping and reduce fall risk.

Chapter 5: General Discussion

5.1 Summary of findings

The primary objectives of this dissertation were to determine, among those with stroke in sub-acute stages of recovery, the prevalence of impaired reactive stepping performance, the association with performance on commonly-used clinical measures, and the potential for clinical uptake of a reactive balance control assessment that may better reveal underlying sources of dyscontrol. Further, this dissertation aimed to explore the temporal characteristics of reactive stepping that could be revealed by such assessment methodologies. Overall, this dissertation affirmed that reactive stepping performance post-stroke is a significant problem not clearly revealed by commonly-used clinical measures of functional balance, mobility or lower-limb impairment. There is the potential for uptake of novel, assessment methodologies within the clinical setting, such as the lean-and-release assessment, for a subset of individuals with stroke who are progressing in their functional mobility status over the course of rehabilitation. Such assessments, when paired with force plate technology, can quantify and reveal determinants of temporal dyscontrol of both the paretic and nonparetic lower-limbs, known to be associated with falls after stroke (Mansfield et al. 2013).

5.1.1. The need for targeted measures of reactive balance control

The risk of falls after stroke is well known (Weerdesteyn et al. 2008) and the link between falls and reactive stepping performance has been recently established (Mansfield et al. 2013; Mansfield et al. 2015c). Of concern, reactive balance control is not routinely assessed within current physical therapist practice (Sibley et al. 2011b). The present studies revealed that the majority of individuals with stroke, preparing for discharge to the community, were profoundly challenged when stepping with both the paretic and nonparetic limb and unable to successfully use reactive stepping to recover balance following instability. The magnitude of this problem has not been previously documented. Given the countless perturbations to balance that occur in daily activities, and that fall rates are known to dramatically increase (up to 73%) upon return to the community (Forster and Young 1995), these findings raise alarm and suggest that this aspect of balance control is worthy of clinical focus in early stages of stroke recovery and rehabilitation.

It is well-known that physiotherapists commonly rely on clinical balance scales that are observation-based and focus on volitional control (Baetens et al. 2009; Blum and Korner-Bitensky 2008; Sibley et al. 2011a). These measures, often referred to as 'functional balance tests' (Mancini and Horak 2010), are typically categorical in nature, assigning numerical values to varying levels of task performance that challenge an individual's balance. Such measures have advantages for use in the clinical setting being psychometrically sound (Blum and Korner-Bitensky 2008), easy to administer and requiring little equipment. Therapists perceive the tests as useful in providing an objective reference to evaluate change in performance over time and with intervention (McGinnis et al. 2009). However, a commonly-cited limitation of functional balance assessments is their inability to provide information on the type of balance problem, in order to direct appropriate treatment (Horak et al. 1997; Horak 2006; Mancini and Horak 2010). Indeed, it is noteworthy that therapists base 'diagnostic' clinical decision-making on qualitative observation of performance, not the findings of these clinical measures (McGinnis et al. 2009). The findings of this dissertation would similarly support that commonly-used clinical measures of balance, mobility, and lower-limb voluntary control may not identify individuals with stroke

who, at time of discharge to the community, had impaired performance of reactive stepping that could put them at risk in this environment. Reactive stepping is fundamentally different than voluntary stepping, initiated and executed markedly faster (Luchies et al. 1999; Martinez et al. 2013; McIlroy and Maki 1996b). Therapists' observations of performance on functional tasks that focus on voluntary movement and under self-selected speed may then provide misleading information related to the individual's balance abilities. The present findings would, therefore, add to existing literature and support the development and clinical use of targeted assessments of reactive balance control.

5.1.2 The potential for clinical uptake of methods to assess characteristics of reactive stepping

Most standardized clinical measures do not include items that assess reactive balance control (Sibley et al. 2015), even fewer include items that independently assess reactive stepping (DePasquale and Toscano 2009; Franchignoni et al. 2010; Horak et al. 2009; Jacobs et al. 2006; La Porta et al. 2011; Padgett et al. 2012; Rose et al. 2006) and, of those available, none are frequently used in practice (Sibley et al. 2011b). Typically, these measures ask the individual to either lean or push against the therapist's hands, who then suddenly releases this support to elicit a reactive step; responses are rated on a 3-point (Franchignoni et al. 2010) or 4 point scale (Horak et al. 2009; Padgett et al. 2012) according to overall ability to recover balance independently. An alternate experimental approach, the instrumented lean-and-release method used in the present research, was developed for use in a stroke rehabilitation setting, as a potentially feasible alternative that could overcome limitations of clinical measures

including safety (Harburn et al. 1993), variability in administration (Jacobs et al. 2006) and more precise quantification of the response (Smith et al. 2014). The present study confirmed the potential for clinical uptake for a subset of individuals admitted to stroke rehabilitation (42% of all admissions). The assessment was administered later in the inpatient rehabilitation stay, to those who had higher levels of cognitive and motor recovery and were progressing in their functional mobility status at greater rates, than those not assessed.

Studies to date, exploring reactive balance control within stroke, have primarily focussed on those with chronic stroke with the ability to walk (Harburn et al. 1993; Marigold et al. 2005; Marigold and Eng 2006; Martinez et al. 2013). An early study exploring the use of cable-pull reactive balance control assessment in those with chronic stroke, suggested that the test was clinically applicable for those who were 'high-functioning' and ambulatory (Harburn et al. 1995). The present research revealed limitations in use of the assessment for those with more profound disability that requires further study (discussed further in sections below); however, it is noteworthy that those assessed had substantial stroke-related impairment. Although direct comparisons to earlier studies cannot be made, the present results suggest it is feasible for quantitative assessments of reactive stepping to be administered to individuals within early stages of stroke rehabilitation (acknowledging the unique setting for this research); in turn, this could allow for the prioritization of interventions that target these important balance-recovery responses at early stages of functional mobility training, to potentially reduce fall risk upon return to the community.

5.1.3 Measurement approaches to specifically reveal underlying temporal dyscontrol

There are a number of studies that have suggested that technological measures can reveal underlying postural dyscontrol after stroke, not detected by observation-based methods (de Haart et al. 2004; Garland et al. 2003; Garland et al. 2007; Kirker et al. 2000; Laufer et al. 2003; Leroux et al. 2006; van Asseldonk et al. 2006). The third study focussed on temporal dyscontrol, specifically early 'time to foot off' phases, because of its association with falls after stroke (Mansfield et al. 2013), evidence that it can be modified (Mansfield et al. 2011) and, therefore, a potentially important target for assessment and treatment. In reaction time stepping, voluntary execution of the paretic limb is slower than the nonparetic limb (Martinez et al. 2013; Melzer et al. 2010). The paretic limb also demonstrates longer, more variable response latencies during reactive feet-in-place responses (Di Fabio et al. 1986; Marigold et al. 2004; Marigold and Eng 2006). In contrast, the present study revealed that response latencies in early phases of balance recovery responses were not significantly different between limbs. However, unique stroke-related impairments differentially influenced timing in early phases of nonparetic and paretic lower limb reactive stepping. The added instrumentation (e.g. force plate technology and load cells) revealed the influence that the capacity to weight shift and load the lower limbs, limb-load asymmetry, and the amplitude of the perturbation, may have on the timing of responses for the paretic limb, the nonparetic limbs, or both, respectively. Further, small delays in the order of milliseconds in the nonparetic limb were associated with increased likelihood of perturbation-evoked falls

The present dissertation has, therefore, made some important contributions to the present body of knowledge and would support the evolution of standardized clinical

assessment methods within stroke rehabilitation that specifically target reactive stepping and, with added instrumentation, can better reveal and quantify underlying dyscontrol that may not be detected by observation of voluntary movement, but is influential to balance recovery responses.

5.2 Key considerations for the evolution and clinical uptake of new approaches to assess reactive balance control

Knowledge translation is a rapidly growing area of science with an aim to determine the most effective approach to move 'knowledge into action' (Sibley et al. 2011a; Sibley and Salbach 2015). A detailed review of the knowledge translation literature, or discussion within the context of this research, is beyond the scope of this dissertation. However, the underpinnings of the present research were grounded in knowledge translation theory. The knowledge-to-action (KTA) framework (Graham et al 2006) provides a stepwise process to support clinical uptake of new research knowledge. The KTA framework (Figure 5.1) divides knowledge translation into two phases: i) the knowledge creation phase, and; ii) the action cycle. The knowledge creation phase involves the synthesis of knowledge into usable units: knowledge gained from primary studies may be synthesized into aggregate knowledge (e.g. systematic reviews) and refined further to knowledge tools (e.g. best practice guidelines). The action cycle identifies the steps required for knowledge to be moved into clinical practice, although these can be dynamic and performed in any order (as indicated by the arrows). The present research was conducted on the background of, and concurrent to, a broader program of research and knowledge translation activities occurring with the research (patient clinic)

setting. Previous research had established that reactive stepping was a critical link to falls (Maki & McIlroy 1999; Maki & McIlroy 2006) (Identify, review, select knowledge) but reactive balance control was not routinely assessed in physical therapy practice (Sibley et al. 2011b) (Identify problem). From results of previous pilot study (Lakhani et al. 2011a), the 'lean and release' method was identified as a potentially feasible, standardized and quantifiable approach to measuring reactive stepping within a stroke rehabilitation setting. Through an iterative process of knowledge exchange, researchers and physiotherapists within the clinical setting collaboratively developed and modified a balance and mobility assessment, including the lean and release assessment, to align with clinical needs (Adapt knowledge to local context; Assess barriers/facilitators to knowledge use; Select, tailor, implement interventions). The assessment evolved to become part of routine care for patients within the inpatient stroke rehabilitation program. An important outcome of this early work was the development of a detailed database (*Evaluate outcomes*) which was the basis for the studies within the present thesis. Study one was able to confirm the need for targeted assessments of reactive balance control within stroke rehabilitation (Identify problem). Study two determined clinical uptake of the lean and release assessment and the clinical profile of the patients with whom it was being used (Monitor knowledge use). Therapist and patient perceptions of the larger balance and mobility assessment, including the lean and release assessment, were explored in a separate study (Pak et al. 2015) (Assess barriers to knowledge use). Features of reactive stepping extracted from the assessment were linked to falls after stroke (Mansfield et al. 2013, 2015c) (Evaluate outcomes) and the temporal characteristics, specifically delays in time to foot off, were associated with falls within inpatient rehabilitation. Study three identified differences in,

and determinants of, time to foot off within the paretic and nonparetic limb (*Knowledge creation*). Collectively, this work can inform the future evolution of quantitative, reactive balance control assessment.



Figure 5.1 The Knowledge to Action Framework. From Graham I, Logan J, Harrison M, Strauss S, Tetroe J, Caswell W, Robinson N: Lost in knowledge translation: time for a map? *The Journal of Continuing Education in the Health Professions* 2006, 26, p. 19. Reprinted with permission from John Wiley and Sons.

Ultimately, the assessment of responses evoked by lean and release perturbation must evolve to be psychometrically sound; providing novel, diagnostic information related to reactive balance dyscontrol that would guide interventions; consistent with the needs of, and acceptable for use by, the patient; and feasible for implementation across clinical settings. Key determinants of knowledge uptake worthy of attention include the attributes of the innovation or practice change, the patient for whom it is intended to benefit, the therapist who is to adopt it, and the context of the practice setting in which it is to be implemented (see figure 5.2) (Bensing 2000; Berwick 2003; Castiglione and Ritchie 2012; Graham et al. 2006; Greenhalgh et al. 2004; Sanson-Fisher 2004). Considerations and recommendations for the future evolution of reactive balance control assessments are discussed below with large focus on the development of the 'innovation' and further standardization of the clinical assessment protocol. Therapist and patient perceptions of the lean-and-release assessment, explored in separate study (Pak et al. 2015), are also considered within the context of the present research findings and future recommendations.



Figure 5.2. Determinants of clinical uptake of new assessment approaches.

Clinical uptake of new assessment approaches to reactive balance control will be influenced by: the attributes of the 'innovation', i.e. the new assessment; the characteristics, preferences and needs of the patient for whom it is intended; the characteristics and perceptions of the adopting therapist, and; the context of the practice setting in which the assessment is to be implemented.

5.2.1 The innovation: Evolution of the clinical assessment protocol

5.2.1.1 The goal of the clinical assessment of reactive stepping

A hallmark of human balance control is the system's remarkable adaptability, based on the individual's goals and prior experience (Burleigh et al. 1994; Horak et al. 1989a; McIlroy and Maki 1995), both in the sensory information used and the motor strategies elicited (Marsden et al. 1981; Nashner 1982; Peterka 2002), depending on the context of the task and the environment (McIlroy and Maki 1993b; Zettel et al. 2002). However, this remarkable feature also poses significant challenge for clinical measurement of reactive balance control.

The 'disturbance-related specificity' of various perturbation methods requires consideration (Grabiner et al. 2008). Different assessment methods can result in different sensory stimuli, perturbation characteristics and degree of predictability that, in turn, could influence the biomechanical and information processing requirements and balance-recovery strategies and responses. The more sensitive the measures being used, the greater potential for results to be influenced by variations in assessment method. Mansfield and Maki (Mansfield and Maki 2009) compared age-related differences in the pattern and spatio-temporal features of reactive stepping across cable-pull and surface translation perturbation methods. The direction of the effect was consistent across methods, however, age-group effects were almost always more pronounced in the surface translation method. Of relevance to the present study, mean time to foot off was substantially faster (> 100 ms) in the surface translation versus the cable-pull method for both the young and elderly.

No assessment method can mimic or measure all possible 'real-world' contexts of instability that might influence an individual's performance. Despite situation-specific characteristics, however, there are 'constants' that an independent method of perturbation can reveal about underlying balance control. One such 'constant' is rapid timing, where applied perturbations, assuming they adequately challenge stability, will evoke reaction and response times that reveal capacity of processing and movement speed. In this light, the goal of the clinical assessment would more feasibly be to measure the individual's *capacity* for reactive stepping. Capacity has been defined as the highest probable level of ability measured in a

standardized environment (World Health Organization 2002), to neutralize the varying impact of different environments, and better allow for the ability to interpret and compare within and across individuals.

5.2.1.2 The perturbation method

A fundamental and initial direction is to determine what clinical assessment protocol should be further developed and 'translated'. Various perturbation methodologies have been used in research, for example, weight-drop and motor-driven cable-pulls (Lakhani et al. 2011a; Martinez et al. 2013), surface translations (McIlroy and Maki 1996a) and treadmill-based perturbations (Owings et al. 2001; Sessoms et al. 2014). The present study used the lean-andrelease approach to induce a balance perturbation. There are obvious limitations to this method; it is limited to a forward fall, therefore, the direction of the perturbation is predictable, although temporal unpredictability is maintained (Hsiao-Wecksler 2008). (The present research also suggested limitations in use for those with greater disability which is discussed in sections below). As previously noted, however, the goal of the clinical assessment would not be to mimic all real-world contexts but, instead, allow for a controlled method to measure the capacity for rapid stepping responses to instability. In the present research, the lean-andrelease method of perturbation, adapted for clinical use, was able to successfully induce reactive stepping responses in individuals within sub-acute stages of stroke recovery, allowing for features of balance responses to be quantified and studied. The rapid time to foot off latencies would also suggest that the induced perturbation was able to evoke rapid reactions, beyond that which can be generated voluntarily (Martinez et al. 2013). Further, the features of

reactive stepping revealed through this assessment have been linked to 'real-life' falls after stroke (Mansfield et al. 2013; Mansfield et al. 2015c), providing some support for the external validity of this approach, despite its ecological shortcomings. It is suggested then that the leanand-release method of perturbation is a viable approach to develop for use in clinical settings to measure reactive stepping capacity after stroke. The present research, however, would also suggest that further standardization of the protocol is warranted to address issues related to variability in administration and individual responses.

5.2.1.3 Tasks and conditions to expose balance dyscontrol

Most individuals step with the nonparetic limb more frequently than the paretic limb to recover balance (Mansfield et al. 2012; Martinez et al. 2013). The present study used an encouraged-use condition to force stepping and allow for assessment of the non-preferred limb and revealed that stepping may be profoundly challenged in both the paretic and nonparetic limb. The inability to step with the non-preferred limb has been found to be predictive of falls after discharge to the community (Mansfield et al. 2015c). The encouraged-use condition also exposed temporal dyscontrol within the paretic limb that has not previously been revealed (Lakhani et al. 2011a; Mansfield et al. 2013; Martinez et al. 2013). Collectively, these findings suggest that clinical assessments of reactive stepping should include conditions that challenge both the paretic and nonparetic limbs, as control issues may not be detected by an evaluation that is limited to only the preferred response.

As previously discussed, the lean-and-release methodology is limited to a forward perturbation. It has been documented that individuals with chronic stroke (Marigold and Eng

2006) and the elderly (Carbonneau and Smeesters 2014; Hsiao and Robinovitch 1998; Troy et al. 2008) are less likely to recover from perturbations that elicit a backwards, rather than a forwards step. Limb collisions have been observed through assessments that impose mediolateral perturbations in those with Parkinson's disease (King and Horak 2008) and this stepping feature has been linked to falls in the elderly (Maki et al. 2001). The addition of backwards or lateral perturbations may then expose different underlying aspects of biomechanical or neuromuscular dyscontrol not revealed by forward perturbations alone. However, few studies have explored backwards (Hsiao and Robinovitch 2001; Telonio et al. 2005) or sideways perturbations (Carbonneau and Smeesters 2014) using the lean-and-release method within healthy populations. Given the substantial challenge observed in reactive stepping post-stroke in response to forward falls, the methodological implications, and the additional burden to the individual associated with performance of additional trials, it is suggested that initial clinical protocols using the lean-and-release method are delimited to a forward fall. Ongoing research could continue to explore responses to alternate tasks and conditions, which may inform future models of this assessment.

5.2.1.4 Perturbation amplitude

Previous studies within the healthy young and elderly (Do et al. 1999; Thelen et al. 1997; Thelen et al. 2000) suggest that temporal features of reactive stepping are influenced by the amplitude of the perturbation. Within the present study, time to foot off was similarly influenced in those with stroke; the greater the cable load, the faster the step was initiated. The

amplitude of the perturbation is, therefore, a key consideration in the development of standardized clinical assessment protocols.

The maximal recoverable lean angle (i.e. the greatest lean angle from which the individual can recover successfully with a single step) is a common criterion used within many lean-and-release studies, to compare differences across healthy young and elderly groups (Do et al. 1999; Grabiner et al. 2005; Madigan and Lloyd 2005b; Thelen et al. 1997; Thelen et al. 2000; Wojcik et al. 1999, 2001). It has been suggested that balance recovery strategies can be more varied at smaller lean angles but are inherently fixed at maximal lean angles (Cyr and Smeesters 2007). To this point, differences in time to foot off (Thelen et al. 2000) and peak joint velocities (Madigan and Lloyd 2005b) between the healthy young and elderly groups have only been revealed when challenged at their maximal recovery abilities. The maximal recoverable lean angle could also be considered as the criterion for perturbation amplitude at the level of individual assessment; the threshold for failed capacity of balance recovery performance could be identified and underlying dyscontrol examined. A reactive step was consistently elicited at mean cable loads of 8% BW. It would then seem reasonable to continue to use this as an initial target perturbation amplitude from which cable load can be titrated upwards or downwards by 2% BW until the individual fails to recover balance twice at that lean amplitude. To assure safety when increasing the lean amplitude, the maximal balance recovery thresholds may first need to be established using the paretic limb and then confirmed, or further titrated, using the nonparetic stepping limb, to determine upper limits of balance recovery. Failure could be defined as: i) trials that required assistance or support from the harness,; ii) multi-step trials, where more than two steps were taken, the second follow-up step with the opposite limb was

30% longer than the participant's body height, or more than one step was taken with the initial stepping limb (Madigan and Lloyd 2005b; Wojcik et al. 2001); iii) use of reach-to-grasp responses, or; iv) an inability to step with the non-preferred limb. It is recognized that those assessed have considerable sensorimotor impairment, that there is anxiety associated with the test (Pak et al. 2015), and that clinicians need to perceive the assessment as an acceptable and safe practice in early stages of stroke recovery. Setting lower and upper limits of perturbation amplitude would then seem appropriate (e.g. titration to a lower threshold of 4-6% BW or upper threshold of 14-16% BW, respectively) to: i) avoid excluding those at lower levels of ability, who may fail to recover balance at even 'small' amplitudes, and; ii) to sufficiently challenge those at higher levels of ability, within acceptable thresholds that approximate the lower limits of maximal balance recovery ability for the healthy elderly (Carbonneau and Smeesters 2014; Wojcik et al. 1999).

5.2.1.5 Instructions

Performance can vary according to the instructions provided. Within the present study, patients were instructed to 'respond however you would naturally to recover your balance'. Other studies have used instructions that constrain the individual, for example, to recover with only a single step, for a consistent performance criterion by which to compare across groups of participants (Madigan and Lloyd 2005a, 2005b; Thelen et al. 1997; Thelen et al. 2000; Wojcik et al. 1999, 2001). The frequency of stepping has been found to be higher when instructions allow for a natural versus constrained response (McIlroy and Maki 1993a). Multiple step responses are common in the elderly (McIlroy and Maki 1996a) and, as the present study reveals,

common in those with stroke. Therefore, one might argue that instructions that constrain the task are measuring a non-instinctive stepping strategy (Wojcik et al. 2001). Cyr and Smeesters (Cyr and Smeesters 2007, 2009) examined the influence of instructions on the balance recovery responses of the healthy young at maximal lean angles. There was negligible effect on the joint torques and spatiotemporal characteristics of the first step and overall maximal balance recovery abilities; they therefore concluded that instructions limiting, or not limiting, the number of steps could be equally valid. Influence of instructions on those with stroke has not been specifically studied. However, as the goal of the clinical test is to assess the individual's balance-recovery capacity, it is suggested that standardized instructions are developed that constrain the task (e.g. 'step as quickly, and with as few steps, as possible to recover your balance and hold this position') such that the participant aims to respond with their highest level of ability with respect to speed and stability.

5.2.1.6 Pre-perturbation limb load

In the present study, pre-perturbation load on the stepping limb, specifically the nonparetic limb, influenced time to foot off. It was also noted that participants were shifting their weight to facilitate stepping with the less loaded limb. Pre-perturbation limb load, therefore, needs to be more carefully controlled. Pre-perturbation limb load was monitored in attempt to have the individual maintain their preferred stance and, therefore, better reflect performance in their 'usual state'. However, as individuals with stroke transition to the community, falls more often occur during dynamic activities, such as walking (Weerdesteyn et al. 2008), where either the paretic or nonparetic limb may be loaded. Although participants adopted an asymmetrical preferred stance, they were noted to have the capacity to maximally load both their paretic and nonparetic limbs, on average, to more than 75% of their body weight. Future methods could, therefore, aim to standardize the pre-perturbation vertical load to 50% body weight on each limb, to control for the influence of pre-perturbation posture. More overt cues (visual or auditory) are required to alert the assessing therapist should the patient shift outside the designated limb-load thresholds. It is acknowledged that equal limb load in a forward lean position for those with stroke may be more challenging than in preferred stance, given the required increase in ankle dorsiflexion. In such cases, pre-perturbation limb load will need to be measured and considered in interpretation of the response.

5.2.1.7 Clinically meaningful measures of reactive stepping

McGinnis and colleagues reported that the information that physical therapists feel they gain from an outcome measure outweighs the time required to administer it (McGinnis et al. 2009). Therapists have previously expressed challenges in interpreting the clinical meaning of technological measures (Pak et al. 2015) and have mixed views as to whether the added information influences, rather than confirms, treatment (Pak et al. 2015). Collectively, this would suggest that is it critical that we continue to advance research to aid in the clinical interpretation and the diagnostic utility of reactive stepping measures, to guide therapy and ultimately improve patient outcomes.

Some important work has started; features of reactive stepping that are linked to falls after stroke have been identified that could be potentially targeted in training (Mansfield et al. 2011; Mansfield et al. 2015a) For example, identifying that an individual is unable to step freely

with both limbs may direct the therapist to include treatment approaches that encourage the use of the non-preferred limb's involvement in reactive stepping (Mansfield et al. 2015c).

However, the value of instrumented clinical assessment approaches would be in their ability to reveal underlying dyscontrol that may otherwise be masked. A critical factor of balance recovery responses is the speed at which they can be executed. The present study focused on timing, specifically in early foot-off phases. Rapid TFO latencies were evoked within both the paretic and nonparetic limbs in response to instability. However, small delays in nonparetic TFO, in the order of milliseconds, influenced the likelihood of a perturbation-evoked fall. Such temporal dyscontrol could not be revealed through observation alone nor inferred through measures of volitional limb control, suggesting the value of adding the force plate measures to the lean-and-release methodology. However, revealing that the individual's paretic limb TFO was 350 ms does not immediately guide clinical decision-making. Further research should identify healthy-age related reference values across perturbation thresholds. Prospective research is required to examine associations of temporal features of reactive stepping with falls, walking independence, levels of activity and participation, from which clinically meaningful threshold values and refined predictive equations can evolve. Finally, although stroke-specific impairments that differentially influenced nonparetic and paretic step timing were revealed in the present study, determinants of temporal dyscontrol warrant further investigation to aid in diagnostic utility. Time to foot off is a composite measure that can be further divided into phases of step onset, anticipatory postural adjustments or swinglimb unloading (Lakhani et al. 2011a). Delays in TFO could be attributed to impaired sensory detection or speed of sensorimotor processing, impaired lateral stability control, or attributed

to the reduced power (produce of force and velocity) of the lower-limb muscles. Future research is, therefore, required to explore phase-specific delays and respective determinants that may differentially focus treatment and improve clinical care and outcomes.

5.2.2 The patient

The lean-and-release assessment of reactive stepping was able to be administered to those in early stages of stroke rehabilitation. However, not all patients were able to complete all trials and conditions (i.e. 5 preferred and 5 encouraged-used trials) and those with greater disability were not assessed. Patient safety (Harburn et al. 1993), anxiety or sense of security (Pak et al. 2015) could influence the uptake of these more challenging assessments. Proposed changes to the clinical protocol may aid in this respect: i) titrating perturbation amplitudes to achieve the maximal balance recovery threshold may require fewer trials to be administered, and; ii) those with greater disability can be tested at lower cable loads, rather than repetitively being tested at a target perturbation amplitude that is resulting in a failed response. Physical therapists and individuals with stroke, who have administered or been exposed to reactive balance control testing, respectively, have advocated for the use of a harness system; patient anxiety was overcome and confidence gained through exposure to safe but challenging balance assessments (Pak et al. 2015). Patient anxiety caused by the reactive assessment was also overcome by the trust placed in their supervising physical therapist (Pak et al. 2015). The leanand-release methodology, therefore, seems to have important features (i.e. overhead harness and footprint that allows for close therapist supervision) that bode well for uptake in clinical practice settings. However, further study is required to explore patient-specific characteristics

that may have influenced administration of the assessment and, further, whether these limitations were specific to the lean-and-release methodology or more generally to any assessment of reactive stepping.

At time of discharge, the mean clinical scores of those not assessed equaled or surpassed the admission scores of those who were assessed. It is possible then that considerations related to patient readiness for assessment juxtaposed with length of stay. Individuals in more acute stages of stroke recovery are being prioritized for inpatient rehabilitation (Meyer et al. 2012), often with more complex presentations (Heart and Stroke Foundation 2014). Rehabilitation assessment practices may need to evolve to address the continuum, rather than discrete episodes, of patient care; assessments conducted near the end of inpatient stay for those slower to recover, may inform care for the next phase of outpatient rehabilitation, to ensure that these important balance-recovery responses are assessed and addressed within the course of rehabilitation.

5.2.3 The therapist

The characteristics of the 'adopting' practitioner and their perceptions of the innovation are important determinants of uptake of new practices (Estabrooks et al. 2003; Greenhalgh et al. 2004; Jette et al. 2003; Salbach et al. 2007; Salbach et al. 2010). Physiotherapists have previously reported that the quantitative data of the assessment is beneficial to patient care, to confirm clinical reasoning and to aid in precise evaluation of progress (Pak et al. 2015). The latter point is noteworthy given that the present findings suggest that the majority of individuals are not reassessed within their inpatient rehabilitation stay. Therapists expressed a

learning curve associated with the interpretation of the data (Pak et al. 2015) and future research to advance the diagnostic utility of the assessment have been discussed in the section above. The unique clinical: research partnership afforded in this setting, and the engagement of front-line therapists in the development and adaptation of the lean-and-release assessment, likely influenced their perceptions and clinical uptake of the assessment; this may limit the generalizability of the present results to other settings. Alternatively, it could be viewed as a positive result of the underlying approach of this research. The meaning of an innovation, its ability to meet an identified need, and its relevance to practice has powerful influence on the adopter's decision (Greenhalgh et al. 2004; Salbach et al. 2010). Integrated knowledge translation (Graham and Tetroe 2007) and strong clinical: research learning partnerships (McWilliam 2007; K. Powell et al. 2013; Thomas and Law 2013) could then be viewed as essential in the evolution of new assessments using measurement technology, to ensure that the end-product that emerges meets the clinical needs of the front-line therapist.

5.2.4 The practice setting

Future evolution of reactive balance control assessments needs to consider factors within the practice setting that could influence uptake including access to resources, required training and time for administration of the assessment. It is suggested that the lean-and-release methodology, of all current methods available, is the more feasible option for clinical implementation. It is recognized, however, that access to the technology associated with this assessment, in its present form, would not be widely available in most clinical settings. It is also recognized that the present results suggesting the potential for clinical uptake, occurred with
additional human resources to operate the equipment and post-process the data to generate the clinical report. Physiotherapists have previously reported that they would not likely perform the assessment if they did not have support to administer the data collection computers (Pak et al. 2015). Hiring of additional support personnel is likely not a feasible option in most clinical settings. More focused efforts towards educating current or future physical therapists may assist in building comfort in use of technology in the clinical setting. However, this will not overcome the commonly-cited barrier of time to administer balance assessments (Sibley et al. 2013), especially in their current, more complex format.

Ultimately, quantitative assessments need to evolve to be low-cost, easily administered in varied practice settings, providing immediate and meaningful information in clinicallyfriendly formats that interface easily with emerging electronic health records. Notably, inexpensive games-based force plates are being advanced (Clark et al. 2010). Rapid advancements in wearable technology are also occurring with application to the clinical setting (Bonato 2005, 2009). Such technology can measure leg and torso motions and have recently been used to measure standing balance control (Mancini et al. 2012). Inertial movement sensors that are small, easily applied, with wireless data transfer capabilities, and with the flexibility to be used in various clinical settings, may pose as feasible, future options in which to devote present development efforts (Smith et al. 2014).

5.3 Limitations

A number of limitations related to the lean-and-release methodology, potential sources of variability in administration and participants' responses, and potential barriers to clinical

101

uptake have been addressed above. Future research to confirm test-retest reliability of both administration variables (pre-perturbation limb load and perturbation amplitude) and response variables (e.g. time to foot off) of the assessment will be important for interpretation at the individual level. The data was derived from a retrospective review of reactive stepping assessments conducted as part of clinical care; however, this approach was purposeful. The clinical protocol was specifically developed in collaboration with front-line therapists and measures collected prospectively, allowing for the development of a detailed clinical database from which data could be extracted retrospectively, to gain new knowledge of balance control within the 'typical' patient. This dissertation proposes revisions to the current clinical protocol that will warrant further evaluation. The present dissertation limited its characterization of reactive stepping responses after stroke to categories of balance-recovery performance (in study one) and time to foot off (in study three). Other spatial and temporal features of reactive stepping post-stroke, not included in the present study, obviously warrant attention and inclusion in the future evolution of clinical assessments. The latter has impact on the measurement approaches/techniques that would be required to assess the potential range of clinically meaningful outcomes associated with balance recovery responses.

5.4 Conclusions

This dissertation aimed to advance understanding of reactive balance control after stroke to inform and guide clinical assessment practices. This dissertation affirmed that reactive stepping performance post-stroke is a significant problem not clearly revealed by commonly-used clinical measures that focus on volitional control. There is the potential for

102

uptake of quantitative assessment methodologies within the clinical setting, such as the leanand-release assessment, for those in early stages of stroke recovery who are progressing in their functional mobility status over the course of rehabilitation. Further, such assessment methods, when paired with kinetic or kinematic measurement technology, can quantify and reveal determinants of temporal dyscontrol of both the paretic and nonparetic lower-limbs, known to be associated with falls after stroke. Further standardization of the clinical protocol is required to address variability in administration and better determine the individual's capacity for reactive stepping and reveal underlying and influential dyscontrol. Evolution of the assessment will necessarily need to consider key determinants of clinical uptake including: the attributes of the assessment; the characteristics, preferences and needs of the patient for whom it is intended; the perceptions of the adopting therapist, and; the resources, training and time required for clinical implementation within the practice setting. Ongoing research is required to continue to refine clinical approaches to reactive balance control assessment that are effective, efficient, relevant to clinical populations and feasible for clinical practice.

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