SIT-TO-STAND PERFORMANCE IN PEOPLE WITH STROKE AND THE EFFECT OF CONSTRAINT-INDUCED MOVEMENT STRATEGIES ON SIT-TO-STAND PERFORMANCE

by

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Abstract

Asymmetry of weight-bearing and impaired ability to maintain centre of pressure in midline contribute to an increased fall risk during sit-to-stand in people with stroke. The main objective of this thesis was to investigate the effect of constraint-induced movement strategies on affected limb weight-bearing and measures of balance in people with stroke. Four studies were conducted to achieve this objective. Study one and two investigated the methodology for describing sit-to-stand performance in people with stroke and reliability of measures of sit-to-stand performance. Findings from study one demonstrated that methods for describing sit-to-stand performance in healthy adults are not feasible in people with stroke and established a method for describing sit-to-stand performance in subsequent studies. Findings from the second study demonstrated within and between day reliability of temporal, weight-bearing and displacement measures of sit-to-stand performance in both groups.

The third study of this thesis described impairments of sit-to-stand performance in people with stroke when compared with healthy age and sex matched adults. The findings confirmed results from previous studies and further described sit-to-stand performance by demonstrating a shift in the frontal plane centre of pressure and centre of mass position toward the unaffected limb at seat-off in people with stroke. The final study investigated the effect of three constraint-induced movement strategies on sit-to-stand performance in people with stroke. The results demonstrated increased affected limb weight-bearing and a shift of the centre of pressure and centre of mass toward midline with all of the strategies. Only two of the strategies altered centre of pressure and centre of mass displacement in the sagittal plane.

Findings from this body of research provide new information regarding the methodology of describing sit-to-stand performance in people with stroke and the reliability of measures of sit-to-stand performance. The results also provide an advanced understanding of sit-to-stand
performance in people with stroke and the effect of constraint-induced movement strategies on sit-to-stand performance. Additional research using constraint-induced movement strategies in a randomized controlled trial will inform clinical practice and may reduce the fall risk in people with stroke.
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<tbody>
<tr>
<td>AP</td>
<td>antero-posterior</td>
</tr>
<tr>
<td>AS-A</td>
<td>asymmetrical-affected</td>
</tr>
<tr>
<td>AS-U</td>
<td>asymmetrical-unaffected</td>
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<tr>
<td>BoS</td>
<td>base of support</td>
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<tr>
<td>CIM</td>
<td>constraint-induced movement</td>
</tr>
<tr>
<td>CIMT</td>
<td>constraint-induced movement therapy</td>
</tr>
<tr>
<td>COM</td>
<td>centre of mass</td>
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<tr>
<td>COP</td>
<td>centre of pressure</td>
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<tr>
<td>COV</td>
<td>coefficient of variation</td>
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<tr>
<td>CVA</td>
<td>cerebrovascular accident</td>
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<tr>
<td>DF</td>
<td>dorsiflexion</td>
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<td>FP</td>
<td>force platform</td>
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<tr>
<td>FPs</td>
<td>force platforms</td>
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<tr>
<td>GCS</td>
<td>global coordinate system</td>
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<tr>
<td>GRF</td>
<td>ground reaction force</td>
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<tr>
<td>IA</td>
<td>index of asymmetry</td>
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<tr>
<td>ICC</td>
<td>intraclass correlation coefficient</td>
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<tr>
<td>IRED</td>
<td>infrared light emitting diode</td>
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<tr>
<td>LCS</td>
<td>local coordinate system</td>
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<tr>
<td>MAD</td>
<td>mean absolute difference</td>
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<tr>
<td>maxAD</td>
<td>maximum ankle dorsiflexion</td>
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<tr>
<td>MDD</td>
<td>minimal detectable difference</td>
</tr>
<tr>
<td>ML</td>
<td>medio-lateral</td>
</tr>
<tr>
<td>MPL</td>
<td>motor performance laboratory</td>
</tr>
<tr>
<td>PRS</td>
<td>plate reference system</td>
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<tr>
<td>SD</td>
<td>standard deviation</td>
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<tr>
<td>SEM</td>
<td>standard error of the measurement</td>
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<tr>
<td>SPO</td>
<td>spontaneous</td>
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<tr>
<td>STP</td>
<td>step position</td>
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<tr>
<td>STS</td>
<td>sit-to-stand</td>
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<tr>
<td>SYM</td>
<td>symmetrical</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>TMK</td>
<td>tracking marker</td>
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<tr>
<td>VGRF</td>
<td>vertical ground reaction force</td>
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Chapter 1

Introduction

1.1 Stroke

Stroke is the third leading cause of death in Canada (1) and is the leading cause of disability in older adults (2). Over 50,000 strokes occur each year and there are approximately 300,000 people living with stroke in Canada (1). Each year, stroke costs the Canadian economy more than 3.6 billion dollars including lost wages, hospital admissions and physician visits (1). Hemiplegia, paralysis or weakness on one side of the body, occurs in 70-85% of people with stroke (3) and 30-40% of people with stroke have disability (4). In addition, people with stroke have a higher risk of falling than their age matched peers with most falls occurring during transition movements including standing up from a seated position (5).

Rising to stand from sitting is one of the most frequently performed tasks of daily living and is considered a prerequisite to functional movement (6). The sit-to-stand (STS) task is complex (6) and biomechanically demanding (7), involving movement of the total body centre of mass (COM) from a large three-point base of support (BoS), including the chair and two feet, to a second smaller two-point BoS, consisting of only the two feet (6). Healthy adults generally perform the STS task without difficulty while maintaining their centre of pressure (COP) close to the midline of the body and placing equal weight on both legs (8-10). Compared with their age and sex matched peers, people with stroke demonstrate weight-bearing asymmetry with greater weight placed through the unaffected limb and increased displacement of the COP in the frontal plane (9-11).

Most falls in people with stroke occur during transition movements including STS (5), which may be attributed to weight-bearing asymmetry and increased COP displacement (10). Cheng et al. (10) reported that the amount of weight-bearing asymmetry and frontal plane COP displacement
increase with disease severity and lead to an increased risk of falling. Consequently, increasing affected limb weight-bearing and improving balance by minimizing frontal plane COP displacement during STS are two common goals of rehabilitation in people with stroke.

One strategy for increasing affected limb weight-bearing during STS in people with stroke is constraint-induced movement therapy (CIMT). Constraint-induced movement (CIM) strategies for the lower limb include placement of the unaffected limb ahead of the affected limb, placement of the unaffected limb on a solid block in parallel with the affected limb and placement of the unaffected limb on a compliant (foam) block in parallel with the affected limb while performing the STS task (8;12-17). Seven studies were found in the literature investigating changes to STS performance in people with stroke using CIM strategies. The focus of investigation in these studies was weight-bearing and joint moment asymmetry with little investigation of possible changes to measures of balance. Only one study was found that investigated changes to COP displacement in the frontal plane using CIM (8). Furthermore, only one study was found that investigated a solid block strategy (15) and one study that investigated a compliant block strategy (12).

1.2 Intent and Structure of Thesis

The primary intent of this thesis is to expand knowledge of STS performance in people with stroke and the effect of CIM strategies on STS performance in this clinical population. Specific measures of interest include time needed to complete the task, affected limb weight-bearing and measures of balance in the frontal and sagittal plane. Investigation of STS performance with CIM strategies in people with stroke will inform clinical practice and provide evidence-based knowledge for clinical decision-making.
Specific objectives of this research include:

1. To investigate the feasibility of using kinetic and kinematic parameters as measures of STS performance in people with stroke and establish a method of performing STS analysis for subsequent studies.

2. To establish the within and between day reliability of temporal, weight-bearing and balance measures of STS performance in healthy adults and people with stroke.

3. To study differences in STS performance in people with stroke and healthy age and sex matched adults using traditional and novel measures.

4. To investigate the effect of CIM strategies on STS performance in people with stroke with specific focus on temporal, weight-bearing and balance measures.

This thesis contains six chapters in addition to the introduction. Chapter 2 of the thesis provides a review of the literature on methods of performing a biomechanical analysis of the STS task. The review also outlines current knowledge of STS performance in healthy individuals and people with stroke with respect to temporal, weight-bearing and balance measures obtained from kinetic and kinematic data. In addition, Chapter 2 outlines current knowledge of CIM strategies designed to promote increased use of the affected limb during STS in people with stroke.

Chapter 3 examines the feasibility of using common measures of STS performance in people with stroke. Concerns with the most common measures of STS performance are discussed and solutions are provided. The method of performing STS analysis in subsequent studies is established.

Chapter 4 examines the within and between day reliability of temporal, weight-bearing and balance measures of STS performance in people with stroke and healthy control participants during STS. Reliability of outcome measures forms the cornerstone of determining the effectiveness of therapeutic intervention. People with stroke demonstrate temporal, weight-
bearing and balance differences and these measures are often reported pre- and post-treatment or when examining the effect of a strategy. However, the reliability of these measures is largely unexplored.

Chapter 5 compares traditional and novel temporal, weight-bearing and balance measures of STS performance in people with stroke and healthy age matched participants. Novel measures are investigated to further describe STS performance in people with stroke and illustrate differences in STS performance compared with healthy adults. An added understanding of differences in STS performance between people with stroke and healthy adults highlighted possible areas for rehabilitation intervention.

Chapter 6 examines the effect of CIM strategies on temporal, weight-bearing and balance measures of STS performance in people with stroke. The intent of this study is to investigate the effect of three CIM strategies on affected limb weight-bearing and determine if the strategies altered frontal or sagittal plane balance measures. Findings from this study will inform decision making related to future intervention studies using these strategies to improve STS performance in people with stroke.

Lastly, Chapter 7 provides an overview of the novel findings from this thesis along with the clinical relevance of the findings. Recommendations based on the findings are outlined along with future research directions.
1.3 References


Chapter 2
Literature Review

2.1 Introduction
This review of the literature will describe the systems and instrumentation required for a comprehensive biomechanical analysis of the sit-to-stand (STS) cycle and the kinematic and kinetic measures most commonly reported. A comprehensive review of current knowledge about STS performance in people with stroke and healthy older adults is included as well as the effect of constraint-induced movement strategies for STS in people with stroke.

The search for peer reviewed publications included the following databases: MEDLINE, EMBASE, CINAHL, AMED and REHABDATA. Search terms describing the STS cycle included: sit to stand, sit-to-stand, rising, and standing. Narrowing the search to inform STS performance in people with stroke included the following search terms: CVA, cerebrovascular accident, hemiplegia and hemiparesis. Additional articles were found by a manual review of the reference list of all articles obtained for inclusion in the review.

2.2 Measurement of STS performance
A comprehensive biomechanical analysis of STS performance requires a motion analysis system and one or more force platforms to obtain kinematic and kinetic data, respectively. Anthropometric data, combined with kinematic and kinetic information, are required for calculation of joint reaction forces and joint moments, as well as the medio-lateral (ML) and antero-posterior (AP) position and movement of the total body centre of mass (COM) of a link segment model within the global coordinate system and in relation to the centre of pressure (COP) (1;2).
2.2.1 Kinematic data

Kinematics refers to the study of motion with no reference to the forces causing motion (1). Kinematic variables include linear and angular displacement, velocity and acceleration. Displacement refers to the change in position within a coordinate system defined during a test session (1). Velocity, the first derivative of displacement, refers to the change in position with respect to time, and acceleration, the second derivative of displacement, refers to the rate of change in velocity with respect to time (1).

Kinematic data is most commonly obtained using a motion capture system, consisting of passive or active tracking markers (TMKs) placed on the body and one or more cameras which record motion of the TMKs during movement (1). Passive TMKs, usually made of reflective material, reflect light directed at the individual performing the motion being studied (1;2). Active TMKs emit infrared light in a sequential pattern captured by a special camera that records movement of the infrared light (2). Tracking markers are placed directly on the skin surface or on rigid plastic plates or probes that are then affixed to the body segment (1). The advantage of mounting markers on a rigid surface is that the markers cannot move independently of one another, which may occur when placed directly on the skin surface due to tissue stretch or compression leading to error in calculation of kinematic variables (1).

Both two-dimensional (2-D) and three-dimensional (3-D) analyses are used to describe the kinematics of the STS cycle. Examples of commercially available motion analysis systems include OPTOTRAK (Northern Digital Inc., Waterloo, Canada), Vicon (Oxford Metrics, Oxford, UK), and Elite (ELITE2002, BTS, Italy). Although the STS cycle predominantly occurs in the sagittal plane, 3-D analysis is most commonly used to provide a detailed description of the motion including linear and angular movement of each body segment in three planes. Three-dimensional motion analysis requires multiple cameras to record the movement of three non-
collinear markers placed on each body segment being analyzed, and a series of calibration points which are used to define the anatomical axis of each segment (1).

Three-dimensional motion analysis requires the definition of two coordinate systems, the global coordinate system (GCS) and the local coordinate system (LCS) (1). The GCS is a fixed reference system; the location and movement of the TMKs are defined relative to the GCS (1). The LCS is a fixed reference system defined by the three non-collinear TMKs on each body segment that move with the segment during motion (1). The LCS and the calibration points, collected during a test session, are used to define the anatomical axis of each segment (1). A series of mathematical rotations define the position of the LCS within the GCS, the position of the anatomical axis in relation to the LCS and finally the position of the anatomical axis within the GCS (1;2).

Definition of the coordinate systems and the anatomical axis of each segment permit the calculation of absolute and relative joint angles. Absolute angles calculate the position of a body segment in reference to the GCS and relative angles calculate the angle between segments (2). For example, the absolute trunk angle may be calculated with respect to the horizontal plane, or as a relative angle between the trunk and pelvis segments (3).

2.2.2 Kinematics of STS
In an example of 2-D STS analysis, passive TMKs placed on the lateral femoral epicondyle, greater trochanter and tip of the acromion were used to determine horizontal and vertical displacement of these anatomical landmarks in the sagittal plane (3). In healthy adults, the lateral femoral epicondyle moved forward and slightly downward at the start of the rising motion followed by backward and slight upward movement (3). Displacement of the greater trochanter was both forward and upward with no movement backward or downward (3). The tip of the
acromion moved forward and upward with slight downward movement at the start of the cycle (3).

Nuzik et al. (3) described the angular displacement pattern at the ankle, knee, hip and trunk in a group of 55 healthy adults. Passive TMKs placed on the fifth metatarsal head, lateral malleolus, lateral femoral epicondyle, greater trochanter, midiliac crest and acromion process defined five segments used to measure the joint angles. Segments were defined by a straight line between two TMKs and included a foot, shank, thigh, pelvis and trunk segment. The foot segment was defined by the two most distal TMKs. The shank segment was defined by the TMK on the lateral malleolus and the lateral femoral epicondyle. The thigh segment was defined by the TMK on the lateral femoral epicondyle and the greater trochanter. The pelvis segment was defined by the TMK on the greater trochanter and the midiliac crest and the trunk segment was defined by the two most proximal TMKs.

At the start and end of the STS cycle the ankle angle, defined by the foot and shank segment, was reported as 105 and 110 degrees, respectively (3). As the subject moved towards the second base of support (BoS) under the two feet, the ankle moved into dorsiflexion followed by a reversal of movement into plantarflexion (3). The knee angle, defined by the shank and thigh segment, was reported as 94 degrees at the start of the cycle (3). When the subject moved forward over the second BoS the knee maintained this position and moved into extension when the subject completed approximately 35% of the overall STS movement (3). At the end of the cycle, the knee angle was approximately 177 degrees of extension (3). The hip angle was reported as 135 degrees at the start of the cycle. The hip angle moved into flexion, reaching a maximum flexion value when the subject completed approximately 40% of the overall STS cycle (3), followed by movement into extension (3). The absolute trunk angle was reported as 80 degrees at the start of the cycle, moved into flexion reaching a maximum flexion angle when the subject completed
approximately 45% of the overall cycle, followed by movement into extension (3). At the end of the cycle the relative hip and absolute trunk angle were reported as 183 degrees and 92 degrees, respectively (3).

Overall, the ankle, hip and trunk angular displacement patterns demonstrate a flexion pattern followed by an extension pattern until full upright standing is achieved. The order of achieving maximum flexion angles was reported as hip, trunk and ankle (4). A peak flexion angle for the knee is not reported because the knee joint only demonstrates movement into extension during STS.

Linear and angular joint velocities are not commonly reported during STS analysis because they are dependent on the speed of movement. Comparison of the linear and angular velocities does little to inform differences in STS performance in populations that inherently perform the task at a slower speed (5). Although joint velocities are not reported for comparison they are used to define the start and end of the STS cycle. For example, the start of the STS cycle was identified when the forward angular trunk velocity exceeded a threshold of 10% of its peak angular velocity, or with the initiation of hip or trunk flexion velocity (5;6).

Linear and angular accelerations are also not commonly reported during STS. However, linear acceleration obtained directly from an accelerometer was used for the purpose of identifying the start and end of the STS cycle by Camargos et al. (7) who placed a triaxial accelerometer on the forehead of all participants and identified the start and end of the STS cycle by the initial change and return to baseline values of the y and z axes of the accelerometer, respectively.

2.2.3 Kinetic data

Kinetics refers to the forces that cause motion (1;2). Kinetic data are most commonly obtained from one of two types of force platforms (FPs) (2). The first type consists of a plate mounted on an instrumented central support and the second type is a plate mounted on four triaxial force
transducers located at the four corners of the FP (2). Kinetic data obtained with the second type of FP is considered more accurate, and therefore this type is preferred for biomechanical analysis of movement (1).

The force applied to the FP by a participant is described by nine variables consisting of the three components of the force vector (Fx, Fy, Fz), the location (x, y, z) of the applied force within the plate reference system (PRS) termed the centre of pressure (COP), and three moments (Mx, My, Mz) (1). Although these nine variables describe the force applied to the FP, kinetics is concerned with the reaction force applied to the participant by the FP (1). Six variables describing the reaction force, obtained from the FP, include the three components of the ground reaction force (GRF) vector (Rx, Ry, Rz), the location of the COP (x, y) and a single moment, termed the free moment (1). The three components of the GRF describe the vertical, anteroposterior (AP) and medio-lateral (ML) forces on the FP (1). The COP describes the location of the GRF within the PRS and the free moment reflects the reaction to the moment applied by the participant to the FP about a vertical axis (1).

Kinetic data are obtained in STS analysis using a configuration of one, two or three FPs (5;8-11). When only one FP is used for analysis it is placed under the two feet (5;8). When two FPs are used in the analysis of STS performance, either one FP is placed under each foot (9), or one FP is placed under the two feet and one FP is placed under the chair (10). When three FPs are used in the analysis, one FP is placed under each foot and one under the chair (11).

A single FP placed under the feet provides a measure of the resultant GRF from both feet and the location of the COP in the plate reference system. A FP placed under each foot permits calculation of the magnitude of the resultant GRF and its location, the COP, separately for each foot. The GRFs from each foot are easily combined using simple addition providing a total GRF. The COP coordinates from each FP are combined using equations reported by Winter (12) to
provide a single COP path representing the path if only one FP was used under the feet, see Equation 1.

\[ \text{Equation 1: COP} = \text{COP1} \left( \frac{Fz1}{Fz2+Fz1} \right) + \text{COP2} \left( \frac{Fz2}{Fz1+Fz2} \right) \]

where COP1 and COP2 are the COP obtained from each FP and the Fz1 and Fz2 are the vertical GRF from the two FPs (12).

Analysis of STS performance with a single FP under each foot allows for comparison of GRFs and the COP coordinates of each foot separately as well as the combined GRF and COP coordinates providing a detailed analysis of the forces causing motion during STS. When three FPs are used in STS analysis a FP is placed under the chair and is used to identify 'seat-off', when the participant loses contact with the chair and transitions to the second BoS consisting of the two limbs (11).

2.2.4 Ground reaction forces and STS

The GRF obtained from a FP has three components, including a vertical, ML and AP component. The vertical GRF (VGRF) component is most commonly reported in STS analysis and is best described by Etnyre et al. (8). The VGRF profile obtained using a FP placed under the two feet in 100 healthy young adults performing the STS task was described by five sequentially observed elements. The five elements include the start of the task, when the VGRF decreased from a baseline value, counter force, the minimum force following the start of the task, peak VGRF, the maximum VGRF following the counter force, rebound force, the minimum VGRF following the peak force and end of the task, when the VGRF visually reached a stable value. The mean and standard deviation VGRF value, normalized to a percentage of body weight, at each of the five elements were reported as 20.6±10.1%, 11.8±10.2%, 116.2±6.9%, 79.6±6.7% and 100±0.3% (8). Figure 2.1 outlines the VGRF profile in Newtons obtained from a healthy young adult.
The GRF in the AP direction, is described as a propulsive force, pushing the participant forward, or a breaking force, minimizing and preventing further forward movement (13). The three elements of the AP GRF profile obtained from 100 healthy young adults performing the STS task described by Etnyre et al. (8) include the start, peak and end of the AP GRF. The peak AP GRF was described as the greatest positive value during the STS cycle (8). The start and end of the AP GRF were described as the points of minimum AP GRF in a negative direction, before and after the peak AP GRF (8). The mean peak AP GRF value, reported as a percentage of body weight, was 9.7± 4.6% (8).

Moving from sitting to standing requires movement of the participant forward and upward, and consequently forces in the ML direction are low and rarely reported. That being said, Etnyre et
al. (8) identified a peak positive and peak negative ML GRF in a group of 100 healthy adults. The peak positive value represented a ML GRF to the right and the peak negative value represented a ML GRF to the left (8). The mean positive and mean negative peak ML GRF values, reported as a percentage of body weight, were 3.1±3.2% and -0.9±2.9% respectively (8).

2.2.5 Centre of pressure and STS

The coordinates of the COP during STS are obtained from one or two FPs. The COP in the ML and AP plane is described as a path (14) and a displacement (15;16). The ML and AP COP path is described as moving toward the left or right of midline or forwards and backwards within the BoS, respectively (14). Displacement of the COP in the ML and AP direction is calculated as the distance between the right and left most lateral positions and between the peak posterior and peak anterior positions, respectively, during the STS cycle (15;16).

The ML path of the COP during STS is not well defined. One study demonstrated that with the feet placed in parallel, the COP moves away from midline toward the dominant limb in the frontal plane in healthy adults (14). Rather than describing the ML COP path during STS, several studies reported the peak-to-peak ML displacement during STS defined as the distance between the most left and right lateral position of the COP between the start and end of the STS cycle. In healthy adults, the mean peak-to-peak ML displacement ranges from 6.1cm to 6.99cm (15-17).

The AP COP path during STS was well described by Schenkman et al. (4) and Riley et al. (9). Schenkman et al. (4) and Riley et al. (9) demonstrated posterior movement of the COP under the feet following the start of the cycle reaching a maximum posterior position when the participant’s buttocks leave the chair. The maximum posterior position was followed by forward movement of the COP, which reached a maximum anterior position immediately following maximum ankle dorsiflexion with a slight posterior movement following the peak anterior COP position (4;9).

Mourey et al. (5) described a similar pattern with the most posterior position of the COP
occurring prior to seat-off followed by forward movement of the COP. Timing of the peak anterior position of the COP in the STS cycle was not well defined by Mourey et al. (5).

The peak-to-peak AP COP displacement was also reported in several studies. In healthy adults, the peak-to-peak AP COP displacement reported by Leroux et al. (16) was 8.18cm; Chou et al. (15) and Cheng et al. (17) reported similar values of 8.6cm and 8.48cm, respectively.

### 2.2.6 Anthropometrics

Anthropometry is the study of physical measurement of the body (2). Anthropometric data, based on cadaveric studies, provides an estimate of segment weight relative to total body weight, the position of the segment COM relative to the proximal and distal end of the segment and the radius of gyration (2). Motion analysis software programs estimate anthropometric data based on the weight (kilograms) and height (meters) of the participant.

Anthropometric data, location of segment COM, combined with kinematic data, location of joint centres and segment length, permit calculation of the position and movement of the total body COM within a multi segment model (2). Combined anthropometric and kinematic data allow calculation of COM displacement within the GCS as well as the velocity and acceleration of the COM during STS. In addition, the position of the COM relative to the COP can be determined when the origin of the FP reference system is established relative to the GCS.

Anthropometric data combined with kinematic and kinetic data permit calculation of joint kinetics including joint reaction forces and net internal moments (2). Measures of kinetic and potential energy can also be determined (2), however these measures are not discussed in this review because they are rarely included in analysis of STS performance. Joint reaction forces and net muscle moments can be described with 2-D or 3-D analysis of the STS cycle.

Three-dimensional analysis requires synchronization of the kinematic and kinetic data both temporally and spatially. Temporal synchronization is completed by motion capture systems,
while spatial synchronization is performed by defining the origin of the FP(s) reference system relative to the GCS (1).

When performing 3-D analysis to determine joint reaction forces and muscle moments, location of joint centres must be established in order to define each segment (1). Joint centres are estimated using a series of calibration points collected during a test session that identify the anatomical landmarks used for estimating the joint centre (1). For example, the ankle joint centre is estimated as the midpoint between the medial and lateral malleoli (1). Location of joint centres is used to define the anatomical axis of a segment and determine segment length and location of the segment COM.

The anthropometric and kinematic data obtained during each frame of movement provide measures of the acceleration of the segment COM and angular acceleration of the segment in the plane of movement. In addition, kinetic data is obtained in each frame of movement from the FP(s). Using Newton’s equations of motion $\Sigma F=ma$ and $\Sigma M=I\alpha$ and a link segment model, the unknown forces and muscle moment acting at the distal and proximal end of each segment can be resolved (2). This method is termed ‘inverse dynamics’ (1;2) and starts with the ankle using the GRFs and the location of the force vector from the FPs. The same equations are then used to calculate moments acting at the knee followed by the hip (2).

2.2.7 Centre of mass and STS

The coordinates of the total body COM within a multi segment model are estimated by locating the coordinates of each segment COM in all three planes of movement. The location of the COM in each plane is multiplied by the weight of the segment and divided by the total mass of the model. See Equation 2 for an example of locating the total body COM in the sagittal plane of a three segment model (2).
Equation 2: \( X_0 = \frac{m_1x_1 + m_2x_2 + m_3x_3}{M} \)

where \( X_0 \) is the location of the total COM of the multi segment model in the sagittal plane, \( m_1, m_2, m_3 \) are the mass of each segment in the model, \( x_1, x_2, x_3 \) are the sagittal plane coordinates of the COM of each segment and \( M \) is the total mass of the multi segment model (2).

The same equation is used to locate the position of the total body COM in the frontal and transverse planes, providing 3-D coordinates of the total body COM in the GCS.

The path of the COM during STS is predominantly described by a forward and upward pattern, with minimal movement downward (9). When the participant initiates movement during the STS, the COM moves forward and slightly downward (9). When the participant begins transfer of weight onto their feet, movement of the COM changes from a forward to a predominantly upward pattern (9).

Displacement of the COM can also be described by the peak-to-peak displacement in the ML and AP planes of movement, however COM displacement is less commonly reported than COP displacement (18).

Riley et al. (9) investigated the timing of peak horizontal and peak vertical COM velocity during STS relative to lift-off and maximum ankle dorsiflexion. The peak horizontal COM velocity occurred at lift-off, when the COM path is predominantly forward. The peak vertical COM velocity occurred after lift-off and at the same time as maximum ankle dorsiflexion, when the COM path is predominantly vertical (9). Riley et al. (9) did not report values of peak horizontal and peak vertical COM velocity.

The peak COM velocity values are not commonly reported or compared between groups during STS analysis because they are dependent on the speed of movement and do little to inform differences in STS performance in populations that inherently perform the task at a slower speed.
(5). Although COM velocity is not compared between groups, changes in COM velocity and peak COM velocity values are occasionally used to identify the start and end of the STS cycle or phases within the STS cycle (9;10;19). For example, Pai et al. (10) identified the start and end of the STS cycle when the COM velocity was greater and less than 7% of its peak value, respectively. Acceleration of the COM is rarely reported in STS analysis.

### 2.2.8 Joint kinetics and STS

Investigation of external flexion-extension moments at the ankle, knee and hip demonstrated that the lowest and highest moments occur at the ankle and hip, respectively at chair heights equal to or less than 100% of the lower leg length (20). Moments at the hip and knee are higher when rising to stand from chair heights less than 100% of the lower leg length, while the ankle moment remains the same (20). When rising to stand from a chair height greater than 100% of the lower leg length, moments at the hip and knee decrease with little to no change in the moment at the ankle (20).

Rodosky et al. (20) reported the mean sagittal plane external moments at the ankle, knee and hip normalized to body weight and height (%body weight x height) in a group of ten young, healthy adults. When rising from a chair height equal to 100% of the lower leg length the mean maximum ankle, knee and hip moments were reported as 30, 50 and 100 (%body weight x height), respectively (20). When chair height was equal to 65% of the lower leg length, the maximum knee and hip flexion moments increased to 60 and 110 (%body weight x height), respectively.

### 2.3 The STS cycle

The STS cycle is defined by a start and end point as well as the event of seat-off when the participant moves from the first BoS to the second BoS. A variety of kinematic and kinetic
parameters are used to identify the start and end of the STS cycle and the seat-off event (4;5;18;21). In addition, two definitions of the end of the cycle are found in the literature (22;23). Several authors defined the end of the task with full upright standing and others defined the end with the return to natural postural sway (4;22;23). Inconsistent methods for defining the start and end of the cycle limit comparison of temporal measures between studies. The variety of parameters used to identify seat-off limit comparison of outcome measures based on the identification of this point in the STS cycle including the VGRF at seat-off or time to seat-off.

2.4 STS in people with stroke

People with stroke have a higher risk of falling than their age matched peers with most falls occurring during transition movements including STS (24). Therefore, examination of STS in people with stroke is critical for understanding the mechanisms underlying the increased risk of falling and the development of strategies to address these mechanisms. The following outlines the current knowledge of STS performance in people with stroke and strategies for improving STS in this clinical population.

2.4.1 Temporal measures

Temporal measures of STS performance include time to complete the cycle and time to complete phases of the cycle (17;18;23).

2.4.2 Total time

Time to complete the STS cycle is longer in people with stroke compared with healthy, age and sex matched control participants (15-17;23). Leroux et al. (16) reported a total movement time of 1.15±0.32 seconds and 1.76±0.55 seconds in a group of healthy control participants and people with stroke, respectively (p<0.05). Galli et al. (23) also demonstrated a longer movement time in
people with stroke (3.89±1.06 sec) compared with healthy control participants (2.42±0.21 sec) (p<0.05).

Values for time to complete the STS cycle in people with stroke ranged from 1.76±0.55 seconds (16) to 4.8±1.6 seconds (15). The range reflects in part, variation in methodology for defining the start and end of the STS cycle and severity of the neurological sequelae following a stroke. For example, Leroux et al. (16) identified the start of the cycle with unloading of the VGRF under the feet and the end of the cycle as the peak VGRF. In contrast, Chou et al. (15) identified the start of the cycle with the word ‘start’ and the end of the cycle when the VGRF under the feet was equal to the participant’s body weight. The methodology used by Leroux et al. (16) underestimated the time to complete the cycle because the peak VGRF occurs close to seat-off, which happens prior to full upright standing. Chou et al. (15) may have overestimated the time to complete the STS cycle because the time to complete the cycle includes the participant’s time to respond to the command to start the cycle.

Cheng et al. (17) examined STS duration in age matched healthy adults, people with stroke who reported no falls (stroke non-fallers) since stroke onset and people with stroke who reported at least one fall (stroke fallers) since stroke onset. Healthy adults performed the STS cycle faster (1.88±.48 seconds) than both groups of people with stroke (p<0.005). The mean STS duration reported in stroke non-fallers (2.73±1.19 seconds) was faster than stroke fallers (4.32±2.22 seconds) (p<0.05).

2.4.3 Phase duration

The STS cycle has been divided into phases in healthy adults and people with stroke. Schenkman et al. (4) provided one of the earliest examples of dividing the STS task into four phases in a group of nine healthy adults. Other studies examining phases of the STS cycle have divided it into two or three phases for analysis (18;23).
Two studies were identified which compared phase duration in age matched healthy control participants and people with stroke (18;23). Hesse et al. (18) divided the STS cycle into two phases. Phase one occurred between the start of the cycle, identified when the combined horizontal force under the chair and feet changed from zero by more than 20% of the peak value for at least 50ms, and seat-off, identified when the VGRF of a FP under the chair was less than 3% of the baseline value. Phase two occurred between seat-off and the end of the STS cycle, identified when the VGRF under the feet was within 5% of the participant’s body weight for at least 100ms. An alpha level of 0.01 was used for all comparisons in this study. Total time to complete the STS cycle was longer in people with stroke compared with age matched healthy adults (p<0.001), however no difference was reported in the occurrence of seat-off, expressed as a percent of the total time, between the two groups (p=0.013).

Galli et al. (23) divided the STS cycle into three phases including the preparation, ascending and stabilization phase. The preparation phase occurred between the start of the cycle, identified with the initiation of forward trunk lean, and seat-off, identified by a pressure sensitive switch placed on the chair to record seat contact. The ascending phase occurred between seat-off and when the participant was standing upright. The authors defined upright standing when all joints were fully extended, however they did not indicate which joints were examined and how full extension was measured. The stabilization phase occurred between upright standing and the end of the cycle. The authors identified the end of the cycle as no fluctuations of movement greater than quiet stance, however they did not indicate if this was determined using kinematic or kinetic measures. Total time to complete the STS cycle was longer in a group of 7 people with stroke compared with a group of 13 healthy adults (p<0.05). Time to complete the preparation and ascending phases were also longer in people with stroke (p<0.05) with no difference in time to complete the
stabilization phase between the two groups. This study reported a mean age of 45.28±7.58 years in people with stroke and 34.54±5.12 years in healthy adults.

2.4.4 Weight-bearing measures

Weight-bearing measures, a reflection of the VGRF, are often reported as a percentage of total body weight (16;25;26). Weight-bearing in people with stroke is reported as the amount of weight on the affected limb or as a difference between the affected and unaffected limb and compared with values in healthy control participants. Affected limb weight-bearing is reported as a percent of total body weight and the difference between the two limbs is reported as a percent of total body weight or as a ratio.

Brunt et al. (25) reported a larger peak VGRF, expressed as a percent of body weight, on the unaffected limb in people with stroke (p<0.05) whereas no difference in the peak VGRF between the two limbs, expressed as a percent of body weight was reported in healthy adults. The percent difference between the two limbs in people with stroke and healthy adults was 16% and 2%, respectively (25). Lecours et al. (27) reported an affected to unaffected limb ratio at seat-off of .67±.26 in people with stroke and a right/left or dominant/non-dominant ratio at seat-off of 1.00±.12 in healthy adults (p<0.001). Similarly, Cheng et al. (17) reported a difference in peak VGRF expressed as a percent of body weight, between the two limbs of 41.86±20.87% in people with stroke and 17.41±5.96% in age matched healthy control participants (p<0.005).

The peak VGRF obtained from the combined VGRF of both limbs, reported as a percentage of body weight, is another measure of weight-bearing. The peak VGRF was found to be lower in people with stroke compared with healthy individuals. Cheng et al. (17) reported a mean value for the maximum VGRF of 114.32±9.06% and 107.19±8.75% of body weight in healthy individuals and people with stroke, respectively (p<0.05).
2.4.5 Displacement measures

Displacement measures of STS performance in people with stroke include COP and COM displacement.

2.4.6 COP displacement

The ML COP displacement during STS is larger in people with stroke compared with healthy control participants (15-17). Cheng et al. (17) reported a mean ML COP displacement of 12.05±6.00cm and 6.73±3.22cm in people with stroke and age matched healthy control participants, respectively (p<0.05). Chou et al. (15) reported a mean ML COP displacement of 9.8±4.1cm and 6.1±2.5cm in people with stroke and age matched healthy control participants, respectively (p<0.01). Leroux et al. (16) reported a mean ML COP displacement of 14.03±2.85cm and 6.99±2.70cm in people with stroke and age matched healthy control participants, respectively (p<0.05).

Variability of ML COP in people with stroke may reflect stroke severity. For example, Cheng et al. (17) examined ML COP displacement in a group of people with stroke who reported no history of falling (stroke non-fallers), and a group who reported at least one fall (stroke fallers). The mean ML COP displacement was larger in stroke fallers 21.05±9.9cm than stroke non-fallers 12.05±6.00cm (p<0.05).

Values of AP COP displacement in people with stroke are reported to be between 7.2±1.19cm and 13.13±7.16cm (14-17;26;28). Only three studies were found comparing AP COP displacement in healthy control participants and people with stroke. Leroux et al. (16) reported no difference in AP COP displacement between people with stroke (7.2.0±1.19cm) and age matched healthy control participants (8.18±2.10cm). Chou et al. (15) also reported no difference in AP COP displacement between people with stroke (9.9±4.4cm) and age matched healthy control participants (8.6±2.1cm). In a third study, Cheng et al. (17) reported no difference in AP
COP between age matched control participants (8.48±2.20cm) and people with stroke (10.23±3.35cm), however, the same study reported a significantly higher AP COP displacement in people with stroke who reported at least one fall since stroke onset (13.13±7.16cm) compared with age matched healthy control participants (p<0.05).

2.4.7 COM displacement

Only one study was found comparing ML and AP COM displacement in people with stroke and age matched healthy control participants during the STS task (18). The ML COM displacement was larger in people with stroke, before and after seat-off during the STS cycle (p<0.001) and (p<0.002), respectively (18). Before seat-off, people with stroke and age matched healthy control participants had a ML COM displacement of 1.6±1.4% height and 0.9±0.6% height, respectively. After seat-off, people with stroke and healthy participants demonstrated a ML COM displacement of 1.8±1.5% height and 1.2±0.9% height, respectively.

Before seat-off, no difference was found in AP COM displacement between people with stroke (8.8±3.5% height) and healthy age matched control participants (8.5±1.3% height) (p=0.517) (18). After seat-off, the mean AP COM displacement was smaller in people with stroke (4.8±2.2% height) compared with healthy control participants (6.4±1.9% height) (p<0.001) (18). Despite no difference in AP COM displacement before seat-off, Hesse et al. (18) reported that in people with stroke the COM was further forward compared with healthy control participants, at the critical point of seat-off. At seat-off the COM was .2cm in front of the heels in people with stroke and was 3.0cm behind the heels in healthy control participants (p<0.001).

2.4.8 Moments

Hip and knee moments have been examined in people with stroke (27;29). Lecours et al. (27) reported the net knee joint moment as a ratio between the affected or non-dominant side and the
unaffected or dominant side in a group of 17 people with stroke and 15 healthy control participants. A smaller knee joint moment ratio was reported in people with stroke (.46±.39) compared with healthy control participants (.98±.24) (p<0.001), demonstrating asymmetry of net knee joint moment in people with stroke (27). The mean age of people with stroke was 49.7±11.3 years and 56.1±10.9 years in healthy control participants.

Roy et al. (29) reported the net knee and hip joint moments of the unaffected and affected limb in the sagittal plane as well as the difference between the two limbs (unaffected side – affected side). At the critical point of seat-off, the net knee joint moment of the unaffected knee (79Nm) was higher than the affected knee (30Nm) (p<0.008) (29). There was no difference in hip joint moment between the affected and unaffected side (p>0.05). At seat-off, the mean difference in knee and hip joint moments between limbs was reported as 47.08±32.40Nm and 7.44±33.00Nm, respectively.

2.4.9 AP force

People with stroke demonstrate asymmetry of the AP force during STS (25). Brunt et al. (25) examined the peak AP force of each limb in people with stroke and healthy adults during STS. The mean age of people with stroke was 65.9 years and 26 years in the healthy adults. This study reported no difference in peak AP force between the dominant (21±7%BW) and non-dominant limb (21±7%BW) in healthy adults and a significant difference in peak horizontal force between the affected (20±5%BW) and unaffected limb (33±14%BW) in people with stroke (p<0.05).

2.4.10 Summary of STS in people with stroke

Overall, people with stroke are slower to perform the STS cycle and demonstrate asymmetry (17;25;27) of weight-bearing, joint moments (27;29) and AP force (25). In addition, people with stroke demonstrate increased displacement of the ML COP and COM (15-18). People with
stroke have a higher risk of falling than their age matched peers (24), with most falls occurring during transition movements, including the STS task (24). Asymmetry and increased displacement of COP and COM may contribute to the increased risk of falling in this clinical population (17). Consequently, goals of treatment for the STS task in people with stroke include reducing asymmetry and ML displacement. One strategy designed to achieve these goals is constraint-induced movement therapy (25;27;30). Constraint-induced movement therapy places the unaffected limb in a position of biomechanical disadvantage, thereby increasing use of the affected limb during the task.

2.5 Constraint-induced movement strategies for STS
Constraint-induced movement strategies designed to promote use of the affected lower limb during STS in people with stroke include placement of the unaffected limb ahead of the affected limb (7;14;31) and placement of the unaffected limb on a solid (30) or compliant (foam) block (25). All three strategies place the unaffected limb in a position of biomechanical disadvantage, promoting increased use of the affected limb (25;30).

2.5.1 Asymmetrical foot position
Placement of the unaffected foot ahead of the affected foot reduced weight-bearing asymmetry, ML COP displacement and knee joint moment asymmetry in people with stroke (14;25;27;29-31). No changes to AP force were reported in people with stroke performing STS with the asymmetrical foot position (25).
Roy et al. (31) examined STS in 12 people with stroke with a mean age of 49.7 years and a range of 27-62 years. The range of time since stroke onset was 6 months to 6 years. The purpose of this study was to investigate the effect of using an altered foot position on the VGRFs during STS in people with stroke. Participants were asked to perform the STS task from an instrumented chair.
equal to 100% of lower leg length measured as the distance from the lateral femoral condyle to
the floor with the subject in a seated position. Four foot positions were used in this study
including a spontaneous (SPO) position where no instruction regarding foot placement was given
to participants, a symmetrical (SYM) position where both ankles were placed in 15 degrees of
ankle dorsiflexion (DF), an asymmetrical-affected (AS-A) position where the affected ankle was
placed in 15 degrees of ankle DF and behind the unaffected foot by half a foot length and an
asymmetrical-unaffected (AS-U) foot position, where the unaffected ankle was placed in 15
degrees of ankle DF and behind the affected foot by half a foot length. The main outcome
measure was weight-bearing asymmetry reported as the index of asymmetry (IA). The IA,
expressed as a percent, provides a measure of the relative amount of weight-bearing on the
unaffected limb (see Equation 3). The IA values range from -100% to +100%. Negative values
represent less weight on the unaffected limb compared with the affected limb and positive values
represent more weight on the unaffected limb compared with the affected limb. A value of 0%
represents equal weight-bearing on the two limbs. The IA was examined at the start of the STS
cycle, the transition point, seat-off and the end of STS cycle. Start of the STS cycle was defined
as the first change of the VGRF under the feet or thigh, the transition point was defined as the
point when forces were similar under the foot and thigh, seat-off was defined when the participant
was just leaving the chair and end of the STS cycle was defined as stable hip extension in
standing.

\[
\text{Equation 3: } IA = \frac{\text{VGRF (foot and thigh combined) on unaffected side} - \text{VGRF of perfect symmetry}}{\text{VGRF of perfect symmetry}}
\]

Where perfect symmetry is defined as 50% of the total VGRF of the unaffected and affected limb
(total VGRF/2)
Across all foot conditions there was no difference in the IA at the start and end of the STS cycle. A significantly smaller IA, reflecting less weight on the unaffected limb, was reported at the transition point and seat-off with the AS-A condition compared with the SPO, SYM and AS-U conditions (p<0.008). The mean IA at the transition point was 10.1±24.9% for the AS-A condition and 24.3±22.1%, 21.4±21.1% and 27.8±18.2% for the SPO, SYM and AS-U conditions, respectively. The mean IA at seat-off was 11.1±20.2% for the AS-A condition and 21.1±16.7%, 20.0±16.3% and 25.6±12.7% for the SPO, SYM and AS-U conditions, respectively.

A second study by Roy et al. (29) investigated the asymmetry of knee and hip joint moments in people with stroke and changes to asymmetry of joint moments using altered foot positions during STS. Asymmetry of joint moments was reported as the difference between sides, unaffected minus the affected side. Joint moment asymmetry was examined at the transition point and at seat-off during the STS cycle, as described above. There was a significant decrease in knee joint moment asymmetry at the transition point and seat-off when performing the STS task with the AS-A foot condition compared with the SPO, SYM and AS-U foot conditions (p<0.001). The mean knee joint moment asymmetry at the transition point was reported as 12.16±24.66Nm for the AS-A condition and 41.97±29.80Nm, 33.72±26.28Nm and 43.76±26.15Nm for the SPO, SYM and AS-U foot conditions, respectively. The mean knee joint moment asymmetry at seat-off was reported as 18.77±37.09Nm for the AS-A condition and 47.08±32.40Nm, 42.50±33.17Nm and 55.89±25.48Nm for the SPO, SYM and AS-U foot conditions, respectively. The hip joint moment was not significantly altered by any of the foot conditions (p>0.05).

Lecours et al. (27) examined STS in 17 people with stroke, with a mean age of 49.7 years, range 27-72 years and the mean time since stroke onset of 3.2 years. The purpose of this study was to examine the effect of foot position on weight-bearing and knee moment asymmetry at seat-off,
defined as the point in the STS cycle when the participant was just leaving the chair. Weight-bearing and knee moment asymmetry were reported as a ratio (see Equations 4 and 5).

\[ \text{Equation 4: weight bearing asymmetry} = \frac{VGRF \text{ affected side}}{VGRF \text{ unaffected side}} \]

\[ \text{Equation 5: knee moment asymmetry} = \frac{knee \text{ moment affected side}}{knee \text{ moment unaffected side}} \]

The foot positions investigated included the SPO, SYM and AS-A, as described above. The mean ratios of weight-bearing asymmetry were 0.67±0.26, 0.66±0.24 and 0.87±0.32 for the SPO, SYM and AS-A foot conditions, respectively. The mean ratios of knee moment asymmetry were 0.46±0.39, 0.46±0.32 and 0.93±0.58 for the SPO, SYM and AS-A foot conditions, respectively. Weight-bearing (p<0.004) and knee moment asymmetry (p<0.05) were lower when performing the STS task with the AS-A foot condition compared with the SPO and SYM foot conditions.

Duclos et al. (14) examined STS performance in 18 people with stroke with a mean age of 50 years, (range 27-73) and a range of time since stroke onset between 6 months and 8 years. The purpose of this study was to investigate the effect of an asymmetrical foot position on ML COP displacement during STS. Participants were asked to perform the STS task from a standardized chair height adjusted to the length of the lower extremity. Two foot positions were examined including a spontaneous (instructions not indicated by author) and asymmetrical position with the unaffected foot placed half a foot length ahead of the affected foot. The ML COP displacement was reduced when performing the STS task with the asymmetrical foot position compared with the spontaneous position (p<0.05). The maximum ML COP deviation from midline toward the unaffected limb was reported as approximately 50mm±10mm and 20±9mm for the spontaneous
and asymmetrical foot positions, respectively (values obtained visually from graphical representation of results).

Brunt et al. (25) examined STS performance in 10 people with stroke with a mean age of 65.9 years, range 37-78 and a range of time since stroke onset between 1 and 10 years. The purpose of this study was to investigate the effect of altered foot placement on the peak vertical and AP GRFs of the affected and unaffected limb during STS. Participants were asked to perform the STS task from a standardized chair height adjusted to the length of the participant’s lower leg, measured as the distance from the lateral knee joint line to the floor. The vertical and AP GRFs were examined using a symmetrical foot position, both knees placed in 100 degrees of flexion and a limb extended position, the affected knee was placed in 100 degrees of flexion and the unaffected knee was placed in 75 degrees of flexion. The mean peak VGRFs for the unaffected and affected limb, reported as a percent of body weight, were 69±14% and 53±9%, respectively for the symmetrical position and 68±17% and 60±11%, respectively for the limb extended position. Peak VGRF was higher for the unaffected limb for the symmetrical position (p<0.05) whereas there was no difference in peak VGRF between limbs in the limb extended position indicating success of the strategy in increasing VGRF under the affected limb. The mean peak AP force for the unaffected and affected limb, reported as a percent of body weight, was 33±14% and 20±5%, respectively for the symmetrical position and 39±12% and 22±8%, respectively for the limb extended position. There was a significant effect of limb for both foot positions (p<0.05) indicating greater AP force on the unaffected limb for both conditions. A main effect for condition was not reported.

Rocha et al. (30) examined STS performance in 13 people with stroke with a mean age of 60 years, range 53-74 years and a mean time since stroke onset of 43.7 months. Participants were instructed to perform the STS task from a standardized chair height equal to 100% of knee height.
Weight-bearing asymmetry was compared across three foot positions included a *spontaneous* (SPO) foot position where no instruction was provided on initial foot position, a *symmetrical* (SYM) foot position where both ankles were placed in 10 degrees of ankle dorsiflexion and an *asymmetrical* (ASY) position where the affected ankle was placed in 10 degrees of ankle dorsiflexion and the unaffected ankle placed forward in 0 degrees of dorsiflexion. Weight-bearing asymmetry of the peak VGRF was reported as the IA and expressed as a percent (see equation 3). The mean IA values for the SPO, SYM and ASY conditions were reported as 25±10%, 24±10% and 18±10%, respectively (values obtained visually from graph). The positive values correspond with greater weight-bearing of the unaffected limb compared with the affected limb. The IA was lower in the ASY condition compared with the SPO (p=0.04) and the SYM (p=0.03) conditions demonstrating reduced weight-bearing asymmetry with the ASY condition.

2.5.2 Solid block strategy
Rocha et al. (30) found that placement of the unaffected foot on a solid block reduced weight-bearing asymmetry during STS in people with stroke. The unaffected limb was placed on a step equal to 25% of the chair height, referred to as the step position (STP). The mean reported IA for the STP position (10±10%) was lower than the IA for the SPO (p<0.001) and SYM (p<0.001) positions. The effect of the STP position on net joint moments and COP or COM displacement were not investigated.

2.5.3 Compliant block strategy
Placement of the unaffected limb on a compliant block did not alter vertical or AP GRF asymmetry in people with stroke (25). Brunt et al. (25) compared the *symmetrical position*, where both knees were placed in 100 degrees of flexion with a *compliant block position*, where the affected knee was placed in 100 degrees of flexion on the surface of the FP and the unaffected
limb placed on a dense foam block equal to 25% of the chair height. The mean peak VGRF, expressed as a percent of body weight, for the unaffected and affected limb was 69±14% and 53±9%, respectively for the symmetrical foot position and 66±12% and 56±12%, respectively for the compliant block position. The peak VGRF for the unaffected limb was higher for the symmetrical and compliant block positions compared to the affected limb (p<0.05). The peak VGRF is greater than total body weight, yielding values greater than 100% (17). Brunt et al. (25) also investigated the mean peak AP force, expressed as a percent of body weight for the unaffected and affected limb. A significant effect of limb was reported for both foot positions (p<0.05). The effect of placing the unaffected limb on a compliant surface on net joint moments and COP or COM displacement were not investigated.

2.6 Concluding remarks
Rising to stand from a seated position is a complex task. A comprehensive analysis of the STS cycle requires kinematic and kinetic data obtained with a 3-D motion analysis system, two or more FPs and anthropometric measurements. The literature review highlights differences in STS performance in people with stroke compared with healthy control participants and the effect of strategies for improving STS performance in this clinical population. The following chapters report on studies that investigate methodological issues when analyzing STS performance in people with stroke and the effect of strategies designed to improve STS performance in this clinical population.
2.7 References


Chapter 3
Sit-to-stand analysis in people with stroke: methodological considerations

3.1 Introduction
Rising to stand from a seated position is a complex task involving transition from a large three-point base of support (BoS) including both feet and the chair to a smaller, two-point BoS consisting of the two feet (1). Analysis of the sit-to-stand (STS) task is important in both healthy and clinical populations including people with stroke because it is the most frequently performed task of daily living and is considered a prerequisite to walking and functional movement (1). People with stroke have a higher risk of falling than their age matched peers, with most falls occurring during transition movements including STS (2;3), demonstrating a need to analyze the STS task in this clinical population.

Two primary methods of describing the STS movement are identified in the literature. The first method divides the STS task into phases (phase analysis) and describes performance of the task within each phase or at the beginning and end of each phase (4). The second method describes performance using discrete points (event analysis) during the STS task (5). Variations of these two methods are used for describing the STS task in people with stroke, however methodological inconsistencies limit comparison of results between studies (6-9).

Division of the STS task into phases is based on the method presented by Schenkman et al. (4). The purpose of this study was to characterize phases of the STS task using kinetic and kinematic data in a group of nine healthy young participants. Using kinetic data and maximum joint angles, the STS task was divided into three phases; the flexion momentum phase (phase one), the momentum transfer phase (phase two) and the extension phase (phase three). A fourth phase, the stabilization phase, was identified but not reported due to difficulty identifying the end of
stabilization and the beginning of natural postural sway. Key events used to define the phases included the start of the task, lift-off, maximum ankle dorsiflexion and the end of the task. Start of the task was identified when the examiner gave the word ‘start’. Lift-off, the marker between phase one and phase two, was identified when the vertical ground reaction force (VGRF) under the feet began to increase in a weight-bearing direction. Maximum ankle dorsiflexion (maxAD), the marker between phase two and three, was identified when maxAD occurred and the end of the task was identified when the hip reached maximum extension. The timing of maxAD of the two limbs was the same in the Schenkman et al. (4) study, suggesting that maximum dorsiflexion of either the right or left ankle could be used to mark the transition between phase two and three.

The duration of phase one, two and three, expressed as a percentage of the overall task from the start of the task to full hip extension, was 28%, 18% and 54%, respectively, in this small group of healthy young adults. In phase one, the trunk and pelvis moved into flexion while maximum trunk-flexion, and hip-flexion angular velocities were achieved. In phase two, maximum ankle dorsiflexion, trunk flexion and hip flexion were achieved as well as maximum hip and knee torques. In addition, there was a transition from angular flexion velocities to angular extension velocities marking a transition of whole body movement from flexion into extension. In phase three, maximum extension velocities were achieved at the knee, hip and trunk.

Etnyre et al. (5) illustrated a second method of describing the STS task by outlining a sequence of kinetic events characterizing the STS task in a group of 100 young, healthy individuals. The STS task was performed with four different arm positions including arms free, arms crossed over the chest, hands on the knees and hands on armrests. A consistent sequence and presence of six events were identified during the STS task, across all four conditions. The events included the start of the task, counter force, seat-off, peak force, post peak rebound force and the end of the task (Figure 3.1). Start of the task was identified when the VGRF under the feet changed from
baseline. The counter force was the reduction in the VGRF under the feet after the start of the task. Seat-off was identified with a voltage-gated switch placed on the chair under the participant’s right ischium. Peak force was identified as the maximum VGRF recorded during the STS task. The rebound force was identified as the minimum VGRF after the peak VGRF. The end of the task was identified visually when the VGRF resembled normal postural sway. All force values were identified from the VGRF of a single force platform placed under the feet.

Figure 3.1: VGRF from a single trial of STS collected in the Motor Performance Laboratory, representing elements outline by Etnyre et al. (5).

The marker of seat-off in both methods present concerns for STS analysis in people with stroke. Schenkman et al. (4) identified lift-off as the point when the VGRF under the feet began to increase in a weight-bearing direction, which does not accurately reflect the transition from the
three-point BoS to the two-point BoS. During the STS task, the VGRF under the feet initially decreases reaching a minimum value followed by a sharp rise. The decrease in the VGRF under the feet corresponds with an increase in the VGRF under the chair. The maximum VGRF under the chair is followed by a sharp decline that corresponds with the sharp increase in the VGRF under the feet. Therefore, the increase in VGRF under the feet in a weight bearing direction corresponds with maximum loading of the chair indicating that the chair is still part of the BoS (10). Etnyre et al. (5), identified seat-off with a voltage-gated switch placed under the participant’s right ischium. When the participant was seated on the chair the switch was closed, when the switch was un-weighted it opened, producing a change in the voltage signal indicating the participant’s body weight was no longer on the chair. Timing of seat-off, when identified by a seat switch, relies upon consistent placement of the switch under the ischial tuberosity in every trial. In addition, people with stroke may asymmetrically unweight their hips as a strategy for completing the STS task. Therefore a switch placed under one ischium may not accurately reflect transition from the three-point BoS to the two-point BoS.

A preferred method for identifying seat-off during STS was described by Roy et al. (10) and Duclos et al. (11). In these studies the transition from the three-point BoS to the two-point BoS was identified when the VGRF on the seat reached zero. This method is preferred because it reflects the change from the three-point BoS to the two-point BoS and does not rely on consistent placement of a seat-switch. Furthermore, Eng et al. (12) demonstrated reliability of total and single limb VGRF measures in people with stroke at this point in the STS cycle, indicating that this is a consistent method of identifying seat-off in this population.

Additional concerns with applying the two methods for describing the STS task in people with stroke include timing of maxAD of the affected and unaffected limb and identification of events in the VGRF trace of people with stroke. Schenkman et al. (4) indicated that the timing of
maxAD of the right and left limb was the same in young healthy participants. However, the
timing of maxAD of the affected and unaffected limb may not be the same in people with stroke
and therefore outcome measures could be dependent of which ankle is used to mark the transition
from phase two to phase three. Etnyre et al. (5) identified events in the total VGRF in healthy
individuals. People with stroke demonstrate weight-bearing asymmetry during STS (13;14) and
studies of STS performance in people with stroke often place a separate force platform under
each limb. Figures observed in Cheng et al. (9), Rocha et al. (7) and Roy et al. (10) suggest that
the events identified by Etnyre are not easily identified in the combined and single limb VGRF
traces of people with stroke.

The purpose of this study was to determine the feasibility of describing STS performance in
people with stroke using phase and event analysis and using a protocol where seat-off is
identified as the point when the VGRF under the chair reaches zero. First, STS data collected in
people with stroke was examined to determine the feasibility of identifying three phases as
described by Schenkman et al. (4) using the preferred method of identifying seat-off. In addition,
the data were examined to determine if the ankle, affected versus unaffected, used for identifying
maxAD influenced the identification and duration of phase two. Second, the combined and single
limb VGRF curves were examined to establish the feasibility of identifying the counter, peak and
rebound events described by Etnyre et al. (5). Force curves were also examined to observe the
timing of peak VGRF in relation to seat-off using the preferred method of identifying this event.

3.2 Methods

3.2.1 Participants
People with stroke were recruited from the community and outpatient programs. Inclusion
criteria were first known stroke, at least three months since stroke onset, only one side of the
body affected by the stroke and the ability to rise from a chair without using their arms. Exclusion criteria included a known history of prior traumatic brain injury, stroke or neurological impairment, known neurological condition affecting the lower limbs other than stroke and lack of awareness of space on the affected side. The university research ethics board approved the study protocol (Appendix A). Prior to participation, the study procedures were explained and participants were given an opportunity to ask questions before providing informed consent. All participants provided informed consent (Appendix B).

3.2.2 Instrumentation
Kinematic data were collected at 50Hz with an OPTOTRAK 3020 system (Northern Digital Inc, Waterloo, Canada) consisting of two arrays of optoelectronic motion tracking cameras. Three AMTI (AMTI, Newton, MA) force platforms were used to gather kinetic data. One force platform was placed under the chair and one force platform was placed under each foot. Kinetic data were collected at 100Hz. Kinematic and kinetic data were temporally synchronized with a motion analysis system (Northern Digital Inc, Waterloo, Canada).

3.2.3 Protocol
Demographic data from each participant were collected prior to the start of the test session to gather information regarding age, time since stroke onset, type of stroke, height and weight to ensure participants met the inclusion criteria. In addition, participants completed a single letter cancellation test to screen for hemispatial neglect (Appendix C). Participants changed into shorts, a t-shirt and a pair of comfortable shoes for testing. Clusters of three or four infrared light emitting diodes (IREDs) mounted on rigid plastic molds were placed bilaterally on top of the foot, lateral mid-shank and lateral mid-thigh. Two additional IRED clusters were placed on the sacrum and at the 7th cervical vertebra. Bilateral marker clusters were secured with Velcro straps.
and reinforced with surgical tape to prevent movement of the clusters during testing. The sacrum cluster was secured with a strap and duct tape and the 7th cervical vertebra cluster was secured with surgical tape.

Subjects were seated on an armless, backless, height adjustable chair with each foot placed on a separate force platform. Chair height was standardized to the height of each participant’s knee, measured as the length between the knee joint line and the floor. The minimum and maximum allowable chair height was 15 and 22 inches, respectively, and adjustable using one-inch increments. The participant’s knee height was rounded up or down to the closest whole number to accommodate the one-inch increment adjustments on the chair. Participants sat with one third of their thigh length on the chair; thigh length was measured as the distance between the greater trochanter and the lateral knee joint line. Feet were placed in parallel with the medial border of the heels 10-15cm apart. Knee angle in sitting was approximately 100 degrees of flexion. Participants were instructed to perform the STS task at a self-paced speed with their arms folded across their chest while looking at a target, placed on a wall 3.7 meters in front of them and 1.6 meters above the floor surface. Tape was placed on the force platforms to promote consistency of foot placement between trials and stickers were placed on the chair and the participant’s thighs to promote consistency of seat position between trials. Participants performed one practice trial of the STS task followed by three trials where data were used for descriptive analysis. Three seconds of baseline data were collected at the beginning of each trial.

At the end of testing participants stood in view of both cameras for collection of a series of reference trials. A pointed probe with four IREDs was used to identify landmarks in relation to the IRED clusters. The four IREDs on the pointed probe were embedded in a fixed orientation to the tip of the probe. Landmarks identified bilaterally with the tip of the probe included the first
and fifth metatarsal heads, lateral and medial malleoli, lateral and medial femoral epicondyles, greater trochanter, a point aligned vertically with each greater trochanter at the level of the anterior superior iliac spine and the acromion process of the scapula.

### 3.2.4 Data Processing and Analysis

Kinematic and kinetic data were filtered (lowpass 6Hz Butterworth) and synchronized using Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD). An eight-segment model was created including the right and left foot, shank, and thigh, the pelvis and the trunk. Segment lengths and joint centers were calculated based on the position of the landmarks (reference trials) in relation to the IRED clusters. Bilateral ankle joint angles were calculated in C-Motion. A combined VGRF was calculated in C-Motion by adding the VGRF value from the force platform under each foot. Synchronized kinematic and kinetic data were exported to Microsoft Excel (Microsoft Office 2002, Microsoft Corporation, USA) worksheets for further analysis.

Four events were identified to establish the feasibility of using phase analysis to describe STS performance in people with stroke. The four events identified include the start of the task, seat-off, maximum ankle dorsiflexion of each limb and the end of the task and these events were used to mark the start and end of three phases. The start of the task was identified visually when the combined VGRF value, obtained from the force platform under each foot, changed from baseline and marked the start of phase one. Seat-off was identified when the VGRF under the chair reached zero and marked the transition between phase one and two. Maximum ankle dorsiflexion of each limb was identified using joint angle values calculated in C-Motion and marked the end of phase two. The end of the task, end of phase three, was identified when the combined VGRF was within five percent of the participant’s body weight for 100ms.
Combined and single limb VGRF curves were examined to determine the feasibility of using *event* analysis to describe STS performance in people with stroke. Three events were identified including the counter, peak and rebound forces. The counter force was identified as the minimum VGRF value after the start of the task. The peak force was identified as the maximum value during the STS task and the rebound force was identified as the minimum value after the peak value. In addition, the force curves were examined to determine the timing of peak VGRF in relation to seat-off when seat-off was identified using the method described above. The start and end of the task were identified using the method described in the previous paragraph.

### 3.3 Results

#### 3.3.1 Participants

Characteristics of the eleven participants are included in Table 3.1. No participant demonstrated evidence of hemispatial neglect with the letter cancellation test. One participant who wore an ankle foot orthosis and one participant with a knee joint replacement were included in the study. The knee joint replacement was on the unaffected limb and occurred five years prior to testing. Three trials were examined for ten of the eleven participants. Two trials were analyzed from one participant due to unusable data in one trial. In total thirty-two trials were analyzed.
### Table 3.1: Participant Characteristics

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<th>Mean or n</th>
<th>SD</th>
<th>Range</th>
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<tr>
<td>Affected side (L/R)</td>
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<td></td>
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<tr>
<td>Age (y)</td>
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<tr>
<td>Time since stroke (y)</td>
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<td>Mass (kg)</td>
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<td>69.90-101.20</td>
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<tr>
<td>Height (m)</td>
<td>1.71</td>
<td>0.06</td>
<td>1.68-1.81</td>
</tr>
</tbody>
</table>

n=11, SD=standard deviation

### 3.3.2 Phase analysis

The average duration of phase one, expressed as a percentage of the overall task was 49.96%.

The average duration of phase two, when maxAD was identified with the affected and unaffected ankle was 6.52% and 6.06%, respectively (Figure 3.2). Maximum dorsiflexion of the affected ankle always occurred after seat-off, providing a range of values for the duration of phase two from 3.34 to 12.56% of the overall task. The percentage of phase two when identified with the unaffected ankle ranged from -2.48 to 10.63%, indicating that maxAD of the unaffected ankle occurred prior to seat-off in at least one trial. Examination of the data revealed that this occurred in the two trials of the participant who had only two trials for analysis. The average duration of phase three with maxAD identified by the affected and unaffected ankle was 43.52% and 43.97%, respectively. Phase three overlapped with phase one in the two trials where maxAD of the unaffected ankle occurred prior to seat-off. Values of phase duration with maxAD identified with the affected and unaffected ankle are presented in Table 3.2.
Figure 3.2: Duration of each phase, expressed as a percentage of the overall task when maximal dorsiflexion of the unaffected and affected ankle is used to define the transition between phase two and three.

Table 3.2: Phase Duration (percentage of the overall task)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Mean (%)</th>
<th>SD (%)</th>
<th>Range (%)</th>
</tr>
</thead>
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<tr>
<td>Phase one</td>
<td>49.96</td>
<td>4.39</td>
<td>44.26 - 57.06</td>
</tr>
<tr>
<td>Phase two (maxAD of affected limb)</td>
<td>6.52</td>
<td>2.60</td>
<td>3.34 - 12.56</td>
</tr>
<tr>
<td>Phase two (maxAD of unaffected limb)</td>
<td>6.06</td>
<td>3.52</td>
<td>-2.48 - 10.63</td>
</tr>
<tr>
<td>Phase three (maxAD of affected limb)</td>
<td>43.52</td>
<td>3.42</td>
<td>39.31 - 48.72</td>
</tr>
<tr>
<td>Phase three (maxAD of unaffected limb)</td>
<td>43.97</td>
<td>4.81</td>
<td>38.92 - 56.75</td>
</tr>
</tbody>
</table>

SD=standard deviation, maxAD=maximum ankle dorsiflexion
3.3.3 Event analysis

3.3.3.1 Combined VGRF
A counter, peak and rebound VGRF were not always easily identified on observation of the force curves as demonstrated in the representative force trace from four participants (Figure 3.3). There was no clearly identified counter force in many of the trials. The peak VGRF did not always occur at the end of the rise in the VGRF (Figure 3.3, CVA03). Multiple peaks were identified in several trials with a smaller peak VGRF preceding or following the true peak VGRF (Figure 3.3, CVA04) or the VGRF leveled off at the end of the rise in the VGRF with no true peak visually identified (Figure 3.3, CVA05). There was no clear rebound in many trials. In several trials, the decline in the VGRF following the peak value was interrupted by an increase in force that was then followed by a second greater decline (Figure 3.3, CVA04).
Figure 3.3: Combined limb VGRF of a single trial from four participants

VGRF=vertical ground reaction force, N=Newtons
3.3.3.2 Single limb VGRF

The counter force was not easily identified in the VGRF trace of the affected and unaffected limb in every trial as demonstrated in the representative force trace from four participants (Figure 3.4). The peak force did not always occur at the end of the rise in the VGRF (Figure 3.4, CVA06 and Figure 3.5, CVA02) and in several trials occurred at the end of the STS task (Figure 3.4, CVA10 and Figure 3.5, CVA06). In addition, the peak force of the affected and unaffected limb did not always occur at the same point in the STS cycle in the same trial. A rebound force was not identified when the peak VGRF occurred at the end of the STS task.
Figure 3.4: Affected limb VGRF from a single trial of four participants

VGRF=vertical ground reaction force, N=Newtons
Figure 3.5: Unaffected limb VGRF from a single trial of four participants

VGRF=vertical ground reaction force, N=Newtons
3.3.3.3 Sequence of seat-off and peak VGRF

Seat-off, when identified by a VGRF of zero under the chair, always occurred following the counter force of the combined VGRF when the counter force was clearly identified in the force trace. Maximum combined VGRF during the STS task occurred at the same time as seat-off in six trials, after seat-off in two trials and before seat-off in the remaining 24 trials. In addition, seat-off always occurred close to the end of the rise in the combined VGRF as demonstrated in the sample graphs in Figure 3.6.
Figure 3.6: VGRF from the force plate under the chair and the combined VGRF under the feet from a single trial of four participants.

VGRF=vertical ground reaction force, N=Newtons
3.4 Discussion
Sit-to-stand performance has been described using three phases as outlined by Schenkman et al. (4). Phases one and three were characterized by joint flexion and extension, respectively. Phase two, the momentum transfer phase, was characterized by maximum hip and knee torques (4), maximum hip and trunk flexion (4), concentric and eccentric muscle activity (15), a sharp rise in the VGRF (15) and control of both forward and upward movement of the COM (15). Given the complexity of phase two, it is often considered the most important phase of the STS task (6;15;16).
Schenkman et al. (4) performed STS analysis in a group of nine, healthy, young individuals. The mean duration of phase one, two and three was 28%, 18% and 54%, respectively, of the overall task. Lift-off, identified when the VGRF under the feet started to increase in a weight bearing direction, marked the transition between phase one and two and maxAD marked the transition between phase two and three. Lift-off, as identified by Schenkman et al. (4), corresponds with the counter force, as identified by Etnyre et al. (5). In the current study a different marker of seat-off was used because it more accurately reflects the transition between the three-point BoS and the two-point BoS and is frequently used in STS analysis (10-12;17).
In the present study, phase one, two and three were 49%, 6% and 43%, respectively. The longer duration of phase one and the smaller duration of phase two, compared with Schenkman et al. (4) is due to a difference in methodology for identifying seat-off and not an indication of a difference in strategy for performing the STS task in people with stroke. Seat-off, as described in the present study occurs after lift-off as identified by Schenkman et al. (4). The shorter duration of phase three in the present study is likely due to a difference in methodology for identifying the end of the task between the two studies.
Duration of phase two is also dependent on timing of maxAD. Schenkman et al. (4) indicated no difference in timing of maxAD of the right and left ankle in young healthy individuals, indicating that maxAD of either ankle could be used to identify the end of phase two. Furthermore, maxAD always occurred following the marker of lift-off. In this study, phase two was not identified in one participant because maxAD of the unaffected ankle occurred prior to seat-off when seat-off was identified by the VGRF under the chair. Consequently both phase two and three overlapped with phase one in both trials from this participant. Maximum ankle dorsiflexion of the affected ankle always occurred following seat-off in people with stroke suggesting that the occurrence of maxAD of the affected ankle may be appropriate to use to identify the end of phase two. However, this may not always be appropriate when foot position is adjusted during the STS task to alter affected limb weight-bearing, thereby altering the timing of the occurrence of maxAD (7;10;18).

Marking the start and end of phase two only provides a measure of phase duration. As demonstrated in this study, phase duration is dependent on methodology and can only be used to examine differences in STS performance when identical methods are used to define phase two in healthy participants and clinical populations. Currently, the literature does not provide consistent identification of phase two thereby limiting comparison between studies (1;4;6). The events characterizing the complexity of the STS task are not lost when phase two is not identified. Rather than reporting the occurrence of maximum joint torques and flexion angles as events in phase two, they could be reported relative to the occurrence of seat-off. Additional measures of STS performance could be reported over the duration of phase one, from the start of the task until seat-off or over the duration of phase two, from seat-off until the end of the task.

STS performance has also been described using event analysis as outlined by Etnyre et al. (5). Etnyre et al. (5) identified six sequential events during the STS task in healthy young individuals performing the task at a self-selected speed. Five events were identified with the VGRF under both feet and a voltage-gated switch placed under the right ischium identified the sixth event,
seat-off. Results from Etnyre et al. (5) suggested that only one counter, peak and rebound VGRF are identified in the combined force trace of both limbs with the peak VGRF occurring at the end of the rise in the VGRF. In addition, the rebound force occurs following an uninterrupted decline in the VGRF after the peak VGRF.

When event analysis was applied to the combined and single limb STS data collected in people with stroke, the peak and rebound forces were not always easily identified. The combined and single limb peak VGRFs did not always occur at the end of the rise in the VGRF. There was often a plateau of the VGRF at the end of the rise in the VGRF and on occasion, the peak VGRF occurred at the end of the STS task. Similarly, the combined and single limb rebound VGRFs were not always easily identified in people with stroke when the VGRF plateaued at the end of the rise in the VGRF and when the decline following the peak VGRF was interrupted by an increase in the VGRF followed by a second greater decline in the VGRF. In some cases, multiple fluctuations in the VGRF were observed prior to the lowest VGRF following the peak VGRF.

People with stroke perform the STS more slowly compared to their age matched peers without stroke (9;11;18). Slower movement leads to lower velocity and acceleration of movement during the STS task. Given the relationship between force magnitude, mass and acceleration, a smaller VGRF magnitude is generated in people with stroke leading to blunting of the counter, peak and rebound forces. Furthermore, the speed of movement and the magnitude of force generated during the STS task may alter timing of the peak VGRF thereby reflecting different strategies for performing the STS task. Therefore, comparison of peak values may be less important than comparison of the timing of peak values.

The peak VGRF is commonly reported in STS analysis and is an indication of the maximum amount of vertical force generated when performing the task in healthy and clinical populations (9). However, it remains unknown if changes to the peak value reflect a different strategy for performing the STS task or is a consequence of impairments associated with a clinical condition such as muscle weakness. From previous studies, it is not always clear if the peak value reported
is the maximum VGRF during the task, the first identifiable peak, or the VGRF at the end of the rise in the VGRF (7-9;13;19;20).

Results from this study demonstrate concerns with identifying and reporting the combined peak VGRF. Etnyre et al. (5) suggested that the peak VGRF occurs at the end of the rise in the VGRF. In people with stroke, it is not always identified at the end of the rise in the VGRF, which may reflect a different strategy for performing the STS. Therefore, comparison of the peak values between populations may not have as much clinical meaning as when it occurs during the STS cycle.

Etnyre et al. (5) did not report single limb peak values, however, comparison of the peak VGRF of each limb is one measure of weight bearing asymmetry in people with stroke (13;21). Results from this study and Rocha et al. (7) demonstrate that within each trial the peak VGRF of the affected and unaffected limb do not always occur at the same point in the STS cycle. Achieving a peak VGRF of the unaffected limb before or after the peak VGRF of the affected limb may reflect a strategy for performing the STS task due to weight-bearing asymmetry. It may be inappropriate to compare the single limb peak values when they occur at different points in the STS cycle because a peak value that occurs close to seat-off may reflect a requirement of the task, while a peak value that occurs close to the end of the task may reflect a strategy for achieving stabilization.

Results from this study demonstrated that seat-off occurs close to the combined limb peak VGRF. The event of seat-off is easily identified during the STS task in people with stroke using VGRF under the chair. Therefore, it may be preferable to report values of VGRF at seat-off to reflect values occurring at the transition of weight-bearing from a three to a two-point base of support.

The STS task involves movement from a three-point BoS and a two-point BoS. Seat-off is a critical point in the STS cycle because it reflects the moment when the person moves from the first to the second BoS. Regardless of strategy, speed of movement and forces generated during the STS task, all participants demonstrate the seat-off event because it is a requirement of the
task. Therefore, it is recommended that temporal, weight bearing and balance measures of STS performance be analyzed in two phases with phase one representing performance within the three-point BoS and phase two representing performance within the two-point BoS. Given the critical point of seat-off it is also recommended that measures of STS performance be reported at this point in the STS cycle with the magnitude and timing of peak values, including peak joint torques, peak force values and peak centre of pressure excursion, being reported in relation to seat-off.

3.5 Conclusions
Phases and events during the STS task as described in the literature are not easily identified in people with stroke and may be the result of a slower speed of movement, generating smaller magnitude of force and using different strategies to perform the STS task due to neurological sequelae of stroke. Based on findings from this study, it is recommended that the STS task be described in two phases in people with stroke, with phase one representing performance from start to seat-off and phase two representing performance between seat-off and end of task. Seat-off, when identified by a VGRF of zero under the chair, reflects the transition from the three-point BoS to the two-point BoS across all participants. Average and peak values of temporal, weight-bearing and balance measures could be reported within each phase. In addition, it is recommended that measures of STS performance be reported at the critical point of seat-off and that timing of peak events be reported in relation to seat-off.
3.6 References


Chapter 4

Reliability of sit-to-stand measures in people with stroke and healthy adults

4.1 Introduction

Stroke is the leading cause of adult neurological disability in Canada (1). Approximately 50-65% of people with stroke will have persistent disability (1) and 88% of people with stroke will have hemiparesis (2). In addition, people with stroke have a higher risk of falling than their age matched peers (3) with most falls occurring during transition movements including the sit-to-stand (STS) task. Consequently, improving STS performance is often a goal of physiotherapy intervention in people with stroke.

Compared with their age matched peers, people with stroke demonstrate weight-bearing asymmetry and impaired balance during the STS task and require more time to complete the task compared with age matched healthy adults (4-7). They also place a greater amount of weight through their unaffected limb and demonstrate increased medio-lateral (ML) centre of pressure (COP) displacement when rising to stand from sitting (4;5;7-9). Both weight-bearing asymmetry and decreased balance may contribute to the increased fall risk in this clinical population (4).

The effect of physiotherapy interventions, including those in people with stroke, is determined by comparing outcome measures assessed before and after a specified training program. Outcome measures must be reliable in order to accurately reflect a true change in performance. Reliability is defined as the repeatability of a measure (10) and is affected by systematic bias and random error (11-13). Systematic bias refers to a non-random change in values between trials or test sessions that occurs in all participants (13). Systematic bias may be observed when all subjects demonstrate the same direction of change in test scores between trials or days. Random error refers to ‘noise’ in the measure; the direction and amount or random error is not consistent across
participants (13). Sources of within and between day systematic error include changes in performance due to a learning effect, fatigue, or motivation (11-13). For example, a systematic decrease in strength scores may occur between trials in a single session due to muscle fatigue from repeated testing. Similarly, a systematic fatigue effect may occur when the participant is not provided with enough rest time between sessions. Sources of random error include biological variability such as changes in the physical or mental state of participants between trials and test sessions, tester error such as decreased attentiveness of the tester between trials regarding patient positioning and instrumentation error (12).

Baseline and post intervention measures of STS performance in people with stroke include temporal, weight-bearing and displacement measures used to reflect time to complete the STS cycle, asymmetry of weight distribution and balance, respectively, during STS. Eng et al. (14) demonstrated reliability of weight-bearing measures during STS in people with stroke, however reliability of other measures in this clinical population has not been examined.

The purpose of this study was to determine within and between day reliability of temporal, weight bearing and displacement STS measures in people with stroke and healthy control participants. All participants visited the Motor Performance Laboratory (MPL) at Queen’s University for testing on two separate occasions one to two weeks apart. Within day reliability is reported for both days of testing to determine which measures demonstrate reliability on each day of testing. Between day reliability is reported to demonstrate which measures demonstrate reliability across the two days of testing.

4.2 Methods

4.2.1 Participants

People with stroke were recruited from the community, outpatient programs and from a list of participants who completed previous studies in the MPL who gave permission to be contacted for future studies. Healthy participants were recruited from the community by word of mouth and
from a list of participants who completed previous studies in the MPL who gave permission to be contacted for future studies. Inclusion criteria for people with stroke were first known stroke, at least six months since stroke onset, only one side of the body affected by the stroke and the ability to rise from a chair without using their arms. Exclusion criteria included a known neurological impairment other than stroke, and lack of awareness of space on the affected side. Healthy adults, age and sex matched to people with stroke, were eligible to participate if they had no known neurological or orthopaedic condition affecting the lower extremities and no known balance or dizziness disorder. The university research ethics board approved the study protocol (Appendix A). Prior to participation, the study procedures were explained and participants were given an opportunity to ask questions before providing informed consent. All participants provided informed consent (Appendix B).

4.2.2 Instrumentation
Kinematic data were collected at 50Hz with an OPTOTRAK 3020 system (Northern Digital Inc, Waterloo, Canada) consisting of two arrays of optoelectronic motion tracking cameras. Three AMTI (AMTI, Newton, MA) force platforms (FPs) were used to gather kinetic data at 100Hz. One force platform (FP) was placed under the chair and one FP was placed under each foot. Alignment and registration of the cameras and FPs was conducted prior to each test session to reference the cameras and FPs to the same coordinate system for comparison of COP and centre of mass (COM) measures.

4.2.3 Protocol
Participants visited the MPL twice, one to two weeks apart for testing of STS performance. On day one, demographic data were collected prior to the start of the test session to ensure participants met the inclusion criteria. Information regarding age, height, and weight were recorded for all participants. For participants with stroke, information regarding time since stroke
onset and type of stroke was also recorded. In addition, participants with stroke completed a single letter cancellation test to screen for hemispatial neglect (Appendix C). For healthy adults, the dominant limb was determined as the limb participants would use to kick a soccer ball. Participants changed into shorts, a t-shirt and a pair of comfortable shoes for testing. Clusters of three or four infrared light emitting diodes (IREDs) mounted on rigid plastic molds were placed bilaterally on top of the foot, lateral mid-shank and lateral mid-thigh. Two additional IRED clusters were placed on the sacrum and at the 7th cervical vertebra. Bilateral marker clusters were secured with Velcro straps and reinforced with surgical tape to prevent movement of the clusters during testing. The sacrum cluster was secured with a strap tied around the participant’s waist with duct tape applied over the edges of the cluster to secure the position on the sacrum. The 7th cervical vertebra cluster was secured directly to the participant’s skin with surgical tape.

Subjects were seated on an armless, backless, height adjustable chair with each foot placed on a separate FP. Chair height was standardized to the height of each participant’s knee, measured as the length between the knee joint line and the floor. The minimum and maximum allowable chair height was 15 and 22 inches respectively and adjustable using one-inch increments. The participant’s knee height was rounded up or down to the closest whole number to accommodate the one-inch increment adjustments on the chair. Participants sat with one third of their thigh length on the chair; thigh length was measured as the distance between the greater trochanter and the lateral knee joint line. Feet were placed in parallel with the medial border of the heels 10-15cm apart. Knee angle in sitting was approximately 100 degrees of flexion. Participants were instructed to perform the STS task at a self-paced speed with their arms folded across their chest while looking at a target placed on a wall 3.7 meters in front of them and 1.6 meters above the floor surface. Tape was placed on the FPs to promote consistency of foot placement between trials and stickers were placed on the chair and the participant’s thighs to promote consistency of seat position between trials. Participants performed one practice trial of the STS task followed by
three trials for analysis. Three seconds of baseline data were collected at the beginning of each trial to provide a baseline measure of the vertical ground reaction force (VGRF) on the chair. At the end of the STS trials, participants stood in view of both cameras for collection of a series of reference trials. A pointed probe with four IREDs was used to identify landmarks in relation to the IRED clusters. The four IREDs on the pointed probe were embedded in a fixed orientation to the tip of the probe. Landmarks identified bilaterally with the tip of the probe included the first and fifth metatarsal heads, lateral and medial malleoli, lateral and medial femoral epicondyles, greater trochanter, a point aligned vertically with each greater trochanter at the level of the anterior superior iliac spine and the acromion process of the scapula.

4.2.4 Definition of the STS cycle
The start of the STS cycle was defined as the first change in the VGRF under the chair from the baseline values. The end of the STS cycle was determined visually when the hip joint of the model created in C-motion reached full extension. Seat-off was defined as the first frame when the VGRF under the chair reached zero.

4.3 Outcome measures

4.3.1 Temporal
1. Time to complete the cycle from start to end (Ttotal), in seconds.
2. Time to complete phase one (Tphase1), in seconds, from the start of the task to seat-off.
3. Time to complete phase two (Tphase2), in seconds, from seat-off to the end of the task.

4.3.2 Weight-bearing
4. Total VGRF at seat-off (WBtotal), in Newtons. The VGRF from the FP under the left and right limb was combined to provide a measure of the total VGRF at seat-off.
5. Affected or non-dominant limb VGRF at seat-off (WB1), in Newtons.
4.3.3 Displacement

6 & 7. Medio-lateral centre of pressure (MLCOP) and medio-lateral centre of mass (MLCOM) displacement in centimeters. The peak-to-peak MLCOP and MLCOM displacement is defined as the distance between the most right and left lateral positions of the COP and COM between the start and end of the STS cycle.

8 & 9. Antero-posterior centre of pressure (APCOP) and antero-posterior centre of mass (APCOM) displacement in centimeters. The peak-to-peak APCOP and APCOM excursion is defined as the distance between the most posterior and anterior positions of the COP and COM between the start and end of the STS cycle.

4.4 Data Processing and Analysis

Kinematic and kinetic data were filtered (lowpass, 6Hz Butterworth) and synchronized using Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD). An eight segment model was created including bilateral foot, shank, and thigh, the pelvis and trunk. Segment lengths and joint centers were calculated based on the position of the landmarks determined during reference trials, in relation to the IRED clusters. A combined VGRF was calculated in C-Motion by adding the VGRF value from the FP under each foot. A combined frontal and sagittal plane COP path was also calculated in C-Motion using the following equation from Winter (15).

\[\text{Equation 1: } COP = COP1 \left( \frac{Fz1}{Fz2+Fz1} \right) + COP2 \left( \frac{Fz2}{Fz1+Fz2} \right)\]

Where COP1 and COP2 are the COP obtained from each FP and the Fz1 and Fz2 are the VGRFs from the two FPs (15).

Synchronized kinematic and kinetic data were exported to Microsoft Excel (Microsoft Office 2002, Microsoft Corporation, USA) worksheets for further analysis. ANOVAs and ICC values were calculated using IBM SPSS Statistics (Version 20).
4.4.1 Within Day Reliability

Statistical analysis was performed on the three trials from day one and day two. Measures of reliability included a repeated measures ANOVA, the intraclass correlation coefficient (ICC\(_{2,1}\)) and the standard error of measurement (SEM) calculated using equation 2 and 3, respectively.

**Equation 2:** \( ICC_{(2,1)} = \frac{MSS - MSe}{MSS + (k-1)MSe + \frac{k(MSE - MSe)}{n}} \)

where \(MSS=\) subjects mean square, \(MSe=\) error mean square, \(MSt=\) trials mean square, \(k=\) number of trials and \(n=\) number of subjects. (12)

**Equation 3:** \( SEM = SD\sqrt{1 - ICC} \)

where \(SD\) is the standard deviation of the scores from all participants equal to the square root of the total sum of squares divided by \(n-1\) (\(n=\) number of participants). (12)

The repeated measures ANOVA was performed to determine if there was a main effect of trial. The ICC was calculated to provide a measure of relative reliability, which reflects the measure’s ability to distinguish among participants in the group. For example, the participant with the lowest score on trial one is expected to have the lowest score across all three trials. The ICC 2,1 model was chosen because it allows for generalization of the reliability of the measures to future studies (12). ICC values greater than .90 and between .70 and .90 will be considered to reflect very high and high reliability of the measure, respectively (10). Values between .26-.49 and .50-.69 will be considered to reflect low and moderate reliability, respectively with values below .26 demonstrating little or no reliability (10).

The SEM was calculated to determine response stability across trials, providing a measure of absolute reliability (10-12;16). Both the SEM and coefficient of variation (COV) provide
measures of absolute reliability (16); the SEM was chosen because it provides a value in the same units as the original measure.

For this study, ICC values greater than .70 were deemed acceptable. Values below .70 were examined for group homogeneity as indicated by the F-test for between subjects effect. A non-significant between subjects effect depresses the ICC value and may lead to a false ICC value (12;16). Threshold values for accepting or rejecting reliability of performance using the SEM were not found in the literature. For the purpose of this study, SEM values less than two standard deviations (SD) of group scores are deemed acceptable. All values were calculated separately for each group of participants.

4.4.2 Between Day Reliability

Statistical analysis was performed on the mean values of three trials from each day and included repeated measures ANOVA, as well as the SEM, the ICC (2,k), the mean absolute difference between days (MAD) and the minimal detectable difference (MDD) as determined using equations 3, 4, 5 and 6, respectively.

Equation 4: \[ \text{ICC}_{(2,k)} = \frac{MS_s - MSe}{MS_s + \frac{k(MSt - MSe)}{n}} \]

where MS_s=subjects mean square, MSe=error mean square, MSt=trials mean square, k=number of trials and n=number of subjects (12).

Equation 5: \[ \text{MAD} = |\text{mean day1} - \text{mean day2}| \]

where mean day1 is the average of three trials on day one and mean day2 is the average of three trials on day two.

Equation 6: \[ \text{MDD} = \text{SEM} \times 1.96 \times \sqrt{2} \]

where 1.96 reflects a 95% confidence interval and the square root of two accounts for the error from the two scores for each participant (12).
The ICC provides a measure of relative reliability and the 2,k model allows for generalization of the reliability of the measure to additional studies (12). The SEM, a measure of absolute reliability, provides a measure of response stability across test sessions (10-12;16). The MAD provides a measure of between day group variability and the MDD provides a measure of the minimal difference needed to reflect a true change in performance (12;16). The MDD estimates for all measures in both groups were calculated with a 95% confidence level to reduce the risk of committing a type one error. The 95% confidence level provides the highest MDD value, it is associated with high specificity, avoiding false positives and low sensitivity, yielding many false negatives (17). Although the 95% confidence level has low sensitivity, interventions based on a false positive result may lead to overtreatment with an ineffective strategy, therefore a 95% confidence level was chosen to minimize the possibility of a type one error.

Between day ICC values were evaluated with the level of acceptability as described for within day ICC values. Acceptable between day SEM values were not found in the literature. The SEM values were compared with the MAD; values within two SDs of the MAD value were deemed acceptable. The MAD is included as a measure of group variability between days and was calculated to determine acceptable SEM values. The MDD reflects the amount of change that is greater than the expected variability in subject scores observed between days. This value is included to establish temporal, weight-bearing and displacement change scores needed to reflect a true change in performance and comment on the use of these measures to assess change over time.

4.5 Results
All participants completed three trials of the STS task on day1 and day2. Due to instrumentation error, the MLCOM and APCOM excursion were not obtained for one participant with stroke on day1. Data from one trial on day1 from a participant with stroke was excluded in the analysis due
to difficulty identifying the start of the STS cycle. In this trial the participant temporarily sat back down on the chair after the initial lift-off of the buttocks from the chair. The mean value from the remaining two trials replaced trial one data for this participant to maintain a sample size of 10 for day 1 within day analysis.

Trial values for each subject and each measure were examined on day 1 and day 2 to identify statistical outliers, defined as a value greater than 3.5 standard deviations from the mean of the remaining two trials (18). All statistical outliers were removed and replaced with a value that was two standard deviations above or below the mean value of the remaining two trials. Outliers higher than the remaining two values were replaced with a value two standard deviations above the mean and outliers less than the remaining two values were replaced with a value two standard deviations below the mean. The trial with the corresponding participant, measure and day of testing identified as statistical outliers are summarized in Table 4.1.

4.5.1 Participants
Ten people with stroke and 10 age and sex matched healthy adults participated in the study. One participant with stroke wore an ankle foot orthosis and another participant with stroke had a knee joint replacement of the unaffected limb five years prior to the study. Participant characteristics are presented in table 4.2.
Table 4.1: Individual trials with values identified as statistical outliers

<table>
<thead>
<tr>
<th>Participant</th>
<th>Measure</th>
<th>Day (1,2)</th>
<th>Trial (1,2,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA01</td>
<td>MLCOP</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CVA01</td>
<td>APCOP</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>HA08</td>
<td>WBtotal</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>HA10</td>
<td>WBtotal</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>CVA07</td>
<td>MLCOP</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>HA03</td>
<td>MLCOP</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>HA03</td>
<td>MLCOM</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>HA06</td>
<td>MLCOM</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adult, APCOP=antero-posterior centre of pressure, MLCOP=medio-lateral centre of pressure, WBtotal=total vertical ground reaction force, MLCOM=medio-lateral centre of mass.

Table 4.2: Participant Characteristics

<table>
<thead>
<tr>
<th></th>
<th>CVA (n=10)</th>
<th>HA (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age(y)</td>
<td>62.40 (9.38)</td>
<td>64.20 (9.91)</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>8/2</td>
<td>8/2</td>
</tr>
<tr>
<td>Mass (kg)*</td>
<td>84.52 (7.85)</td>
<td>74.35 (10.49)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.71 (.07)</td>
<td>1.77 (0.12)</td>
</tr>
<tr>
<td>Affected or non-dominant limb (R/L)</td>
<td>7/2</td>
<td>1/9</td>
</tr>
<tr>
<td>Time since stroke onset(y)</td>
<td>6.09 (10.24)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* there was a significant difference between groups for mass (p<0.05). Abbreviations: CVA=participant with stroke, HA=healthy adult.
4.5.2 Within Day Reliability

4.5.2.1 Temporal measures

The six ANOVAs performed on the temporal measures for people with stroke demonstrated no main effect of trial (p>0.05), demonstrating consistency of performance across trials. The F tests and corresponding p values are summarized in Table 4.3. The ICC values on day1 and day2 ranged from .83 to .91, demonstrating high to very high reliability. All SEM values were smaller than 2 SDs of the corresponding mean value supporting the high reliability estimates of temporal measures in this clinical population. The mean (SD), ICC and SEM values for within day reliability in people with stroke are summarized in Table 4.4.

Table 4.3: F and p values for ANOVAs performed on within day (day1 and day2) temporal measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2)</td>
<td>p</td>
<td>F (9,2)</td>
<td>p</td>
</tr>
<tr>
<td>Ttotal</td>
<td>.267</td>
<td>.769</td>
<td>1.910</td>
<td>.177</td>
</tr>
<tr>
<td>Tphase1</td>
<td>2.679</td>
<td>.096</td>
<td>.582</td>
<td>.569</td>
</tr>
<tr>
<td>Tphase2</td>
<td>.339</td>
<td>.717</td>
<td>2.275</td>
<td>.132</td>
</tr>
</tbody>
</table>

Abbreviations: Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.
Table 4.4: Mean (SD), ICC and SEM values for within day (day1 and day2) temporal measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) (sec)</td>
<td>ICC (sec)</td>
</tr>
<tr>
<td>Ttotal</td>
<td>2.92 (.62)</td>
<td>.91</td>
</tr>
<tr>
<td>Tphase1</td>
<td>1.14 (.21)</td>
<td>.83</td>
</tr>
<tr>
<td>Tphase2</td>
<td>1.78 (.47)</td>
<td>.85</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.

For healthy adults, the six ANOVAs performed on the temporal measures demonstrated no main effect of trial (p>0.05), demonstrating consistency of performance across trials. The F test and corresponding p values are summarized in Table 4.5. The ICC values on day1 and day2 ranged from .60 to .87, demonstrating moderate to high reliability. All SEM values were smaller than 2 SDs of the corresponding mean value. The SEM values support the moderate to high reliability estimates of temporal measures in healthy adults. The mean (SD), ICC and SEM values for within day reliability in healthy adults are summarized in Table 4.6.
Table 4.5: F and p values for ANOVAs performed on within day (day1 and day2) temporal measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2)</td>
<td>p</td>
<td>F (9,2)</td>
<td>p</td>
</tr>
<tr>
<td>Ttotal</td>
<td>.554</td>
<td>.584</td>
<td>.196</td>
<td>.824</td>
</tr>
<tr>
<td>Tphase1</td>
<td>2.684</td>
<td>.095</td>
<td>.015</td>
<td>.985</td>
</tr>
<tr>
<td>Tphase2</td>
<td>.071</td>
<td>.931</td>
<td>.408</td>
<td>.671</td>
</tr>
</tbody>
</table>

Abbreviations: Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.

Table 4.6: Mean (SD), ICC and SEM values for within day (day1 and day2) temporal measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean(SD) (sec)</td>
<td>ICC</td>
<td>SEM (sec)</td>
<td>Mean(SD) (sec)</td>
</tr>
<tr>
<td>Ttotal</td>
<td>2.36(.37)</td>
<td>.87</td>
<td>.25</td>
<td>2.28(.43)</td>
</tr>
<tr>
<td>Tphase1</td>
<td>0.97(.12)</td>
<td>.85</td>
<td>.09</td>
<td>0.91(.15)</td>
</tr>
<tr>
<td>Tphase2</td>
<td>1.38(.33)</td>
<td>.84</td>
<td>.24</td>
<td>1.37(.36)</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.

4.5.2.2 Weight-bearing measures

For people with stroke, the four ANOVAs performed on the weight-bearing measures demonstrated no main effect of trial (p>0.05), demonstrating consistency of performance across trials. The F test and corresponding p values are summarized in Table 4.7. The ICC values ranged from .84 to .96 for weight bearing measures on day1 and day2, demonstrating high to very
high reliability of these measures. All SEM values were smaller than 2 SDs of the corresponding mean value, supporting the high to very high reliability estimates of weight-bearing measures in people with stroke. The mean (SD), ICC and SEM values for within day reliability in people with stroke are summarized in Table 4.8.

Table 4.7: F and p values for ANOVAs performed on within day (day1 and day2) weight-bearing measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2)</td>
<td>p</td>
</tr>
<tr>
<td>WBtotal</td>
<td>.086</td>
<td>.918</td>
</tr>
<tr>
<td>WB1</td>
<td>2.260</td>
<td>.133</td>
</tr>
</tbody>
</table>

Abbreviations: WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the affected.

Table 4.8: Mean (SD), ICC and SEM values for within day (day1 and day2) weight-bearing measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) (N)</td>
<td>ICC (N)</td>
</tr>
<tr>
<td>WBtotal</td>
<td>898.61(83.54)</td>
<td>.92</td>
</tr>
<tr>
<td>WB1</td>
<td>407.81(68.16)</td>
<td>.93</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the affected limb.
For healthy adults, the four ANOVAs performed on weight-bearing measures demonstrated a main effect of trial (p<0.05), for WBtotal on day1. All other ANOVAs demonstrated no main effect of trial (p>0.05) demonstrating consistency of performance across trials. The F test and corresponding p values are summarized in Table 4.9. The ICC values across both days ranged from .90 to .99 demonstrating high to very high reliability of weight bearing measures. All SEM values were smaller than 2 SDs of the corresponding values supporting the high to very high reliability estimates of weight-bearing measures in healthy adults. The mean (SD), ICC and SEM values for within day reliability in healthy adults are summarized in Table 4.10.

Table 4.9: F and p values for ANOVAs performed on within day (day1 and day2) weight-bearing measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2) p</td>
<td>F (9,2) p</td>
</tr>
<tr>
<td>WBtotal</td>
<td>4.227 .031</td>
<td>.653 .533</td>
</tr>
<tr>
<td>WB1</td>
<td>2.103 .151</td>
<td>.778 .474</td>
</tr>
</tbody>
</table>

Abbreviations: WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the non-dominant limb.
Table 4.10: Mean (SD), ICC and SEM values for within day (day1 and day2) weight-bearing measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>ICC</td>
</tr>
<tr>
<td></td>
<td>(N)</td>
<td></td>
</tr>
<tr>
<td>WBtotal</td>
<td>818.49(109.04)</td>
<td>.99</td>
</tr>
<tr>
<td>WB1</td>
<td>399.76(57.95)</td>
<td>.90</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the non-dominant limb.

4.5.2.3 Displacement measures
For people with stroke, the eight ANOVAs performed on the four displacement measures, MLCOP, APCOP, MLCOM, APCOM, demonstrated no main effect of trial (p>0.05), demonstrating consistency of performance across trials. The F test and corresponding $p$ values are summarized in Table 4.11. The ICC values ranged from .52 to .95 on day1 and day2, demonstrating moderate to very high reliability of displacement measures in a single test session. All SEM values were smaller than 2SDs of the corresponding values. The SEM values support the moderate to high reliability of displacement measures in people with stroke. The mean (SD), ICC and SEM values for within day reliability in people with stroke are summarized in Table 4.12. The between subjects effect for MLCOM day1 and day2 was significant, indicating that the moderate ICC values were not the result of homogeneity of participant scores.
Table 4.11: F and p values for ANOVAs performed on within day (day1 and day2) displacement measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2)</td>
<td>p</td>
<td>F (9,2)</td>
<td>p</td>
</tr>
<tr>
<td>MLCOP</td>
<td>1.749</td>
<td>.202</td>
<td>1.499</td>
<td>.250</td>
</tr>
<tr>
<td>APCOP</td>
<td>.912</td>
<td>.419</td>
<td>.244</td>
<td>.786</td>
</tr>
<tr>
<td>MLCOM*</td>
<td>.013</td>
<td>.987</td>
<td>.238</td>
<td>.791</td>
</tr>
<tr>
<td>APCOM*</td>
<td>2.961</td>
<td>.081</td>
<td>1.508</td>
<td>.251</td>
</tr>
</tbody>
</table>

*df (8,2). Abbreviations: MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.

Table 4.12: Mean (SD), ICC and SEM values for within day (day1 and day2) displacement measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD)</td>
<td>ICC</td>
<td>SEM</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td>(cm)</td>
<td>(cm)</td>
<td>(cm)</td>
<td>(cm)</td>
</tr>
<tr>
<td>MLCOP</td>
<td>8.75(5.13)</td>
<td>.93</td>
<td>2.42</td>
<td>6.07(3.36)</td>
</tr>
<tr>
<td>APCOP</td>
<td>9.01(2.62)</td>
<td>.89</td>
<td>1.57</td>
<td>8.77(2.21)</td>
</tr>
<tr>
<td>MLCOM*</td>
<td>2.46(1.07)</td>
<td>.61</td>
<td>1.37</td>
<td>2.22(0.90)</td>
</tr>
<tr>
<td>APCOM*</td>
<td>25.71(2.53)</td>
<td>.88</td>
<td>1.59</td>
<td>25.43(3.47)</td>
</tr>
</tbody>
</table>

* n=9. Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.
For healthy adults, the eight ANOVAs performed on the displacement measures demonstrated no main effect of trial (p>0.05), demonstrating consistency of performance across trials. The F test and corresponding $p$ values are summarized in Table 4.13. The ICC values ranged from .29 to .74, demonstrating low to high reliability of these measures in healthy adults. The SEM values were smaller than 2 SDs of the corresponding value, except MLCOP on day1. The SEM values support the low to high reliability within day estimates of displacement measures in healthy adults. The mean (SD), ICC and SEM values for within day reliability in healthy adults are summarized in Table 4.14. The between subjects effect for MLCOP and MLCOM on day1 was not significant indicating that the low ICC value is partly explained by homogeneity of participant scores. The between subjects effect for all other ICC values below .70 was significant, indicating that the value is not the result of homogeneity of participant scores.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1 F (9,2)</th>
<th>Day 1 $p$</th>
<th>Day 2 F (9,2)</th>
<th>Day 2 $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCOP</td>
<td>.251</td>
<td>.781</td>
<td>1.495</td>
<td>.251</td>
</tr>
<tr>
<td>APCOP</td>
<td>2.016</td>
<td>.162</td>
<td>.038</td>
<td>.962</td>
</tr>
<tr>
<td>MLCOM</td>
<td>.213</td>
<td>.810</td>
<td>1.561</td>
<td>.237</td>
</tr>
<tr>
<td>APCOM</td>
<td>1.855</td>
<td>.185</td>
<td>1.000</td>
<td>.388</td>
</tr>
</tbody>
</table>

Abbreviations: MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.
### Table 4.14: Mean (SD), ICC and SEM values for within day (day1 and day2) displacement measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1 Mean(SD) (cm)</th>
<th>Day 1 ICC</th>
<th>Day 1 SEM (cm)</th>
<th>Day 2 Mean(SD) (cm)</th>
<th>Day 2 ICC</th>
<th>Day 2 SEM (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCOP</td>
<td>4.66(.84)</td>
<td>.29</td>
<td>1.72</td>
<td>4.93(1.42)</td>
<td>.38</td>
<td>2.61</td>
</tr>
<tr>
<td>APCOP</td>
<td>9.11(1.85)</td>
<td>.74</td>
<td>1.82</td>
<td>9.02(1.55)</td>
<td>.62</td>
<td>.96</td>
</tr>
<tr>
<td>MLCOM</td>
<td>1.62(.72)</td>
<td>.34</td>
<td>1.38</td>
<td>1.76(.78)</td>
<td>.43</td>
<td>1.33</td>
</tr>
<tr>
<td>APCOM</td>
<td>28.55(2.14)</td>
<td>.57</td>
<td>2.93</td>
<td>27.83(1.80)</td>
<td>.48</td>
<td>1.30</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.

### 4.5.3 Between Day Reliability

#### 4.5.3.1 Temporal measures

For people with stroke, the three ANOVAs performed on temporal measures demonstrated no main effect of day (p>0.05), demonstrating consistency of performance between the two days of testing. The F test and corresponding p values are summarized in Table 4.15. The ICC values ranged from .65 to .76, demonstrating moderate to high reliability. The SEM values for the three temporal measures were within 2 SDs of the MAD values supporting the moderate to high reliability estimates of temporal measures. The MDD values for Ttotal, Tphase1 and Tphase2 were 1.28, .42 and 1.03sec, respectively, indicating the change score for each measure that reflects a true change in the respective temporal measure. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.16.
Table 4.15: F and p values for ANOVAs performed on between day temporal measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,1)</td>
<td>p</td>
</tr>
<tr>
<td>Ttotal</td>
<td>.054</td>
<td>.822</td>
</tr>
<tr>
<td>Tphase1</td>
<td>.249</td>
<td>.630</td>
</tr>
<tr>
<td>Tphase2</td>
<td>.212</td>
<td>.656</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adult, Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.

Table 4.16: ICC, SEM, MAD (SD) and MDD values for between day temporal measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>SEM</td>
</tr>
<tr>
<td></td>
<td>(sec)</td>
<td>(sec)</td>
</tr>
<tr>
<td>Ttotal</td>
<td>.76</td>
<td>.46</td>
</tr>
<tr>
<td>Tphase1</td>
<td>.65</td>
<td>.15</td>
</tr>
<tr>
<td>Tphase2</td>
<td>.75</td>
<td>.37</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adult, ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MAD=mean absolute difference, MDD=minimal detectable difference, Ttotal=time to complete the sit-to-stand cycle from start to end, Tphase1=time to complete phase one, Tphase2=time to complete phase two.
For healthy control participants the three ANOVAs performed on temporal measures demonstrated no main effect of day (p>0.05), indicating consistency of performance across the two test sessions. The F test and corresponding p values are summarized in Table 4.15. The ICC values ranged from .81 to .84 demonstrating high reliability of temporal measures in healthy adults. The SEM values are all within two SDs of the MAD values supporting the high reliability estimate of temporal measures. The MDD values for Ttotal, Tphase1 and Tphase2 are .69, .22 and .58sec respectively, indicating the change score required to reflect a true change in temporal measures of STS performance. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.16.

4.5.3.2 Weight-bearing measures
The two ANOVAs performed on the weight-bearing measures in people with stroke demonstrated no main effect of day (p>0.05) for WBtotal, indicating consistency of performance for this measure. The ANOVA for WB1 demonstrated a significant effect of day (p=0.021). A paired t-test revealed a smaller WB1 score on day1 407.81±68.16N compared with day2 421.62±74.16N. The F test and corresponding p values are summarized in Table 4.17. The ICC values ranged from .96 to .99, demonstrating very high reliability of weight-bearing measures. All SEM values are within one SD of the MAD supporting the high reliability estimates of these measures. The MDD values for WBtotal and WB1 are 32.38N and 39.69N respectively, providing change scores required to reflect a true change in these measures. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.18.
Table 4.17: F and p values for ANOVAs performed on between day weight-bearing measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA F (9,1)</th>
<th>p</th>
<th>HA F (9,1)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBtotal</td>
<td>1.028</td>
<td>.337</td>
<td>.338</td>
<td>.575</td>
</tr>
<tr>
<td>WB1</td>
<td>7.845</td>
<td>.021</td>
<td>.177</td>
<td>.683</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adult, WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the affected or non-dominant limb.

Table 4.18: ICC, SEM, MAD (SD) and MDD values for between day weight-bearing measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA ICC (N)</th>
<th>SEM (N)</th>
<th>MAD (N)</th>
<th>MDD (N)</th>
<th>HA ICC (N)</th>
<th>SEM (N)</th>
<th>MAD (N)</th>
<th>MDD (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBtotal</td>
<td>.99</td>
<td>11.68</td>
<td>10.71(8.45)</td>
<td>32.38</td>
<td>.98</td>
<td>21.72</td>
<td>20.26(18.56)</td>
<td>60.20</td>
</tr>
<tr>
<td>WB1</td>
<td>.98</td>
<td>14.32</td>
<td>15.55(13.65)</td>
<td>39.69</td>
<td>.96</td>
<td>17.29</td>
<td>18.24(14.41)</td>
<td>47.93</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adults, ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MAD=mean absolute difference, MDD=minimal detectable difference, WBtotal=total vertical ground reaction force, WB1=vertical ground reaction force of the affected or non-dominant limb.
For healthy control participants, the two ANOVAs performed on the weight-bearing measures demonstrated no main effect of day (p>0.05) indicating consistency of performance between day one and day two. The F test and corresponding p values are summarized in Table 4.17. The ICC values ranged from .96 to .98, providing very high reliability estimates of weight-bearing measures. The SEM values were within 2 SDs of the corresponding MAD values, supporting the very high reliability estimates of these measures. The MDD values for WBtotal and WB1 are 59.82N and 47.93N respectively, providing the change scores required to reflect a true change in performance. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.18.

4.5.3.3 Displacement measures
The four ANOVAs performed on the displacement measures in people with stroke demonstrated no main effect of day (p>0.05) demonstrating consistency of performance between the two test sessions. The F test and corresponding p values are summarized in Table 4.19. The ICC values ranged from .63 to .96, demonstrating moderate to high reliability of displacement measures in people with stroke. All SEM values were within 2 SDs of the corresponding MAD values supporting the moderate to high reliability estimates. The MDD values for MLCOP, APCOP, MLCOM and APCOM were 10.32, 2.13, 1.05 and 6.21cm respectively, providing the magnitude of change required to reflect a true change in performance. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.20. The between subjects effect for MLCOP was significant, indicating that the ICC value is not influenced by homogeneity of participant scores.
Table 4.19: F and p values for ANOVAs performed on between day displacement measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA F (9,1)</th>
<th>p</th>
<th>HA F (9,1)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCOP</td>
<td>3.33</td>
<td>.101</td>
<td>.333</td>
<td>.578</td>
</tr>
<tr>
<td>APCOP</td>
<td>.447</td>
<td>.521</td>
<td>.023</td>
<td>.883</td>
</tr>
<tr>
<td>MLCOM</td>
<td>3.068*</td>
<td>.118*</td>
<td>.568</td>
<td>.470</td>
</tr>
<tr>
<td>APCOM</td>
<td>.059*</td>
<td>.814*</td>
<td>1.312</td>
<td>.282</td>
</tr>
</tbody>
</table>

*df (8,1). Abbreviations: CVA=participant with stroke, HA=healthy adult, MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.

Table 4.20: ICC, SEM, MAD (SD) and MDD values for between day displacement measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA ICC</th>
<th>SEM (cm)</th>
<th>MAD(SD) (cm)</th>
<th>MDD (cm)</th>
<th>HA ICC</th>
<th>SEM (cm)</th>
<th>MAD(SD) (cm)</th>
<th>MDD (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCOP</td>
<td>.67</td>
<td>3.72</td>
<td>3.02(3.60)</td>
<td>10.32</td>
<td>.39</td>
<td>1.30</td>
<td>1.05(0.99)</td>
<td>3.60</td>
</tr>
<tr>
<td>APCOP</td>
<td>.95</td>
<td>0.77</td>
<td>0.93(0.56)</td>
<td>2.13</td>
<td>.66</td>
<td>1.41</td>
<td>1.34(1.05)</td>
<td>3.91</td>
</tr>
<tr>
<td>MLCOM</td>
<td>.93*</td>
<td>0.38</td>
<td>0.40(0.34)</td>
<td>1.05</td>
<td>.83</td>
<td>.44</td>
<td>.44(.46)</td>
<td>1.22</td>
</tr>
<tr>
<td>APCOM</td>
<td>.72*</td>
<td>2.24</td>
<td>1.67(2.06)</td>
<td>6.21</td>
<td>.65</td>
<td>1.68</td>
<td>1.72(1.14)</td>
<td>4.66</td>
</tr>
</tbody>
</table>

*n=9. Abbreviations: CVA=participant with stroke, HA=healthy adults, ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MAD=mean absolute difference, MDD=minimal detectable difference, MLCOP=medio-lateral centre of pressure, APCOP=antero-posterior centre of pressure, MLCOM=medio-lateral centre of mass, APCOM=antero-posterior centre of mass.
In healthy control participants, the four ANOVAs performed on the displacement measures demonstrated no main effect of day (p>0.05) demonstrating consistency of performance between days. The F test and corresponding p values are summarized in Table 4.19. The ICC values ranged from .39 to .75, demonstrating low to high reliability of these measures. The SEM values were within 2 SDs of the corresponding MAD values demonstrating acceptable SEM values. The MDD values for MLCOP, APCOP, ML.COM and APCOM are 3.6, 3.91, 1.22 and 4.66cm, respectively, providing the magnitude of change score required to reflect a true change in performance. The ICC, SEM, MAD (SD) and MDD values for between day reliability are summarized in Table 4.20. The between subjects effect for MLCOP, APCOP and APCOM was not significant, indicating that the ICC values are partly explained by homogeneity of participant scores.

4.6 Discussion

4.6.1 Temporal measures
The temporal measures of STS performance, described in this study, met the within and between day reliability criteria in people with stroke. The high within day reliability of temporal measures of STS performance on day1 and day2 demonstrates the trial-to-trial stability of these measures across three trials. Therefore, it is appropriate to use the mean of three trials for analysis. The between day reliability results in people with stroke demonstrates stability of the measure between test sessions when there is no known change in the participant's condition or intervention provided and that changes in these measures exceeding the MDD observed after an intervention are likely due to the intervention and not between day variability in the measure. The between day reliability estimates are lower than within day estimates, suggesting that temporal measures of STS performance may be influenced by sources of random error including the time of testing, the amount of sleep the participant had the night before the test session or changes in the participant’s medication.
All temporal measures met the within day reliability criteria in healthy adults, demonstrating that is it acceptable to use the mean of three trials in analysis of STS performance and for comparison with clinical populations including people with stroke. The between day reliability results in healthy adults met all of the outlined criteria, demonstrating stability of the measure between test sessions when there is no known change in the participant’s condition or intervention. Furthermore, changes to scores exceeding the MDD following an intervention are likely due to the intervention and not variability of the measure between test sessions. The between day reliability estimates in healthy adults are higher than those observed in people with stroke suggesting that temporal measures in healthy adults are not as easily influenced by sources of random error such as fatigue and mental state during testing.

4.6.2 Weight-bearing measures
The weight-bearing measures met the within day reliability criteria for people with stroke. The weight-bearing measures also met the between day reliability criteria except for weight-bearing on the affected limb (WB1). The between day ANOVA for WB1 indicated a significant effect of day with a mean increase on day2. The mean difference between days was 13.81N. Converted into a measure of mass, this value equals 1.41kg. The difference of 1.41kg between days does not reflect a clinically meaningful change in performance and may be the result of familiarity or comfort with the equipment and testing procedures on day2. We aimed to reduce error due to increased comfort with the testing procedures by providing participants with one to three practice trials before recording STS performance on day1 and by recruiting participants familiar with the MPL and equipment used in motion analysis. Given the high ICC values, the small change between days and the acceptable SEM values for WB1, this measure is acceptable to use in future studies with the recommendation that participants be given ample opportunity to practice the task and become familiar with the equipment and procedures prior to collecting trials for evaluation.
People with stroke demonstrate weight-bearing asymmetry with more weight placed through the unaffected limb during STS compared with the affected limb (4;8;9). Consequently, affected limb weight-bearing is a common measure of STS performance in people with stroke (19). Findings from this study agree with those reported by Eng et al. (14) demonstrating reliability of weight-bearing measures in people with stroke. Furthermore, the high reliability of weight-bearing measures of STS performance provide confidence that changes in the measure greater than the MDD after an intervention are likely due to the intervention and not variability of the measure between test sessions.

Weight-bearing measures met the within and between day reliability criteria in healthy adults. Within day reliability results demonstrate stability of the measure across three trials and the acceptability of evaluating the mean of three trials. Between day reliability results demonstrate stability of the measures between test sessions without any change in the participant’s condition or intervention.

Similar to people with stroke, weight-bearing measures of STS performance in healthy adults are not influenced by sources of random error. Healthy adults tend to place equal amount of weight on each limb during STS (8;9), therefore this measure has less clinical significance in healthy adults compared with people with stroke. However, weight-bearing measures of STS performance may have clinical significance in people recovering from hip or knee replacement surgery, people with knee or hip osteoarthritis or in people with a lower limb amputation. Stability of weight-bearing measures provides confidence that changes to the measure exceeding the MDD reflect a true change in performance and not variability of the measure between test sessions.
4.6.3 Displacement measures

Measures of displacement met the within day reliability criteria in people with stroke. These measures also met all of the between day reliability criteria demonstrating stability of the measure between test sessions without any change in the participant’s condition or intervention.

COP and COM displacement are used to measure balance during STS with the ML and AP components reflecting balance control mechanisms in the frontal and sagittal plane, respectively. The high within day reliability of MLCOP and APCOP demonstrates the appropriateness of using these measures to investigate the effect of strategies designed to alter STS performance in a single test session and to compare baseline performance between people with stroke and healthy adults or other clinical populations.

The COM displacement, obtained indirectly by combining anthropometric and kinematic data, demonstrates higher within day reliability in the sagittal plane (APCOM) than in the frontal plane (MLCOM) in people with stroke. The lower reliability results for the within day MLCOM measure on day1 and day2 likely reflect variability in performance and not error in the method of measurement. The between day reliability of the APCOM measure is high indicating that it is acceptable for measuring change over time. The between day reliability for the MLCOM measure is very high suggesting that the variability of the measure observed on day1 and day2 remains stable between days and that this measure could be used to examine change over time.

The MDD estimates for displacement measures are large in people with stroke. MDD values for displacement measures were not found in the literature for comparison, however one study was found that demonstrated a significantly lower MLCOP and APCOP after a three-week training program (20). The baseline and post-training mean MLCOP were reported as 10.9±5.0cm and 7.8±4.2cm respectively (p<0.01). The baseline and post-training mean APCOP was reported as 10.8±4.1cm and 8.8±3.0cm, respectively (p<0.05). The change in MLCOP between baseline and post-training was smaller than the MDD value obtained in this study, suggesting that the MDD value may be inaccurate. Fulk et al. (21) demonstrated that heterogeneity of group scores in a
people with stroke lead to larger MDD values. In a group of 35 participants with stroke, the mean gait speed and MDD estimate was .45±.30m/sec and .30m/sec, respectively. When divided into a group of participants who required physical assistance for ambulation (n=13) and participants who do not (n=22) the group mean values and MDD estimates changed. The mean gait speed and MDD estimate for the group of participants requiring physical assistance was .26±.18m/sec and .07m/sec respectively. The mean gait speed and MDD estimate for the group who did not require physical assistance with ambulation was .56±.30m/sec and .36m/sec respectively.

In the current study attempts were made to reduce the biological variability in people with stroke through the inclusion and exclusion criteria. However, the neurological sequelae following stroke varies between individuals. Although all participants with stroke were able to perform the STS task without using their arms, the group may have differed in muscle strength, sequencing of muscle contraction during STS and overall functional ability. Consequently, the large MDD value for MLCOP may be due to heterogeneity of group scores. The MDD value for APCOP was within the range observed in the intervention study.

In healthy adults, displacement measures of STS performance met the within day reliability criteria except the MLCOP on day1. ICC values ranged from low to high. One possible reason for the low ICC values for MLCOP (.29) and MLCOM (.34) is homogeneity of subject scores. The F-test for between subjects effect must be significant for a valid ICC value (16). The F-test for MLCOP and MLCOM on day1 was not significant, demonstrating homogeneity of scores between individuals. The low ICC values, and homogeneity of group scores suggest that these are not appropriate measures for investigating differences within this group of individuals. However the day1 MLCOM SEM value is within 2SDs of the corresponding mean value and the day1 MLCOP is only .04cm greater than 2 SDs of the corresponding mean value demonstrating absolute reliability of these measures. Therefore, these measures may still be appropriate for investigating differences between this group of participants and a clinical population.
One possible reason for larger variability between trials on day1 could be due to lack of familiarity or comfort with the testing procedures. This study aimed to increase comfort with the testing procedures by recruiting participants who had experience with motion analysis capture equipment from participation in previous studies. In addition, participants were provided with up to three practice trials prior to collecting data. Within day reliability may be improved with further practice of the task on day1 prior to performing the task for evaluation. Furthermore, the testing procedures were standardized for all participants to minimize variability of displacement measures. Chair height was standardized to the length of the participant’s lower leg, marks were placed on the chair and the participant’s thighs to maintain consistency of the seated position and tape was placed on the force platforms marking the medial border of each foot to promote consistency of foot placement.

All measures met the between day reliability criteria indicating, that it is acceptable to use these measures to assess changes to balance over time or with intervention in healthy adults. The relative reliability of balance measures in healthy adults was low to high. One possible reason for the low to moderate results is homogeneity of group scores. The F-test for between subjects effect was not significant for MLCOP, APCOP and APCOM demonstrating similarity of scores amongst participants. Healthy adults perform the STS task with weight-bearing symmetry and with the COP and COM close to the midline in the frontal plane. (4;5;7-9;22). Therefore, it is not surprising to find little variation in scores between individuals, leading to lower ICC values. The absolute reliability met the outlined criteria indicating the consistency of scores between days demonstrating the acceptability of using these measures to assess change over time. The between day reliability result for APCOP was high despite low within day reliability, suggesting that the day1 and day2 variability of the measure remains stable between days and that this measure could be used to examine change over time.
4.7 Conclusions

To our knowledge this is the first study examining within and between day reliability of temporal, weight-bearing and displacement measures in people with stroke and healthy adults as well as the MDD values for these measures. Findings from this study demonstrate within and between day reliability of temporal and weight-bearing measures in both groups and recommend providing people with stroke several practice trials to increase familiarity with the task prior to data collection to reduce between day differences in affected limb weight-bearing. The results from this study demonstrate within and between day reliability of displacement measures of STS performance in people with stroke. The within and between day reliability of displacement measures in healthy adults met the outlined criteria. Despite low ICC values for two of the displacement measures in healthy adults, the SEM values met the outlined criteria demonstrating reliability of these measures and acceptability of comparing the measures between people with stroke and age and sex matched healthy adults. For future investigation of reliability of measures of STS performance in healthy adults it is recommended, when possible, to include participants with a range of ability to increase heterogeneity of participant scores.
4.8 References


Chapter 5

Sit-to-stand performance in people with stroke and healthy adults

5.1 Introduction

People with stroke have a higher risk of falling than their age matched peers with most falls occurring during transition movements including sit-to-stand (STS) (1). Inability to safely and independently stand-up from sitting could lead to the possibility of sustaining a hip fracture from a fall and placement in a care facility (2). Therefore, it is essential to investigate and understand differences in STS performance between people with stroke and healthy adults and develop strategies designed to increase safety and independence of STS in this clinical population.

The STS task involves movement of the body centre of mass (COM) both forward and upward (3). During this task the body transitions from a large three-point base of support (BoS) including the chair and the two feet to a smaller and less stable two-point BoS of the two feet (3). The transition between the first and second BoS occurs when the participant’s buttocks leave the chair, a point commonly referred to as seat-off (4-6). Seat-off is a critical moment when rising to stand from sitting because it marks the point in the STS cycle when the participant’s full body weight is on the two feet. Frequently used measures of STS performance in people with stroke include time to complete the task, weight-bearing asymmetry and centre of pressure (COP) displacement in the sagittal and frontal plane (7-10).

Performance of the STS task, measured from the start to the end of the STS cycle, requires more time in people with stroke than healthy age and sex matched adults (7;8;10;11). When the STS cycle was divided into phases for analysis, Galli et al. (11) reported a longer mean time, to complete the preparation (start of task to seat-off) and ascending phases (seat-off to upright standing) of the STS cycle in people with stroke (p<0.05) with no difference in time to complete the stabilization phase (upright standing to no further fluctuations in movement) between the two groups. In the study by Galli et al. (11) seat-off was identified when pressure sensitive switches
placed on the chair were off. Findings from Chapter 3 led the author to recommend that the STS task be analyzed in two phases divided by seat-off as identified by a vertical ground reaction force (VGRF) of zero from a force platform under the chair. This study will determine if there is a difference in the time to complete each phase between people with stroke and healthy adults using methodology outlined in Chapter 3.

People with stroke demonstrate weight-bearing asymmetry with a greater amount of weight placed on the unaffected limb when performing the STS task (7;12;13). Weight-bearing, reported as a percentage of body weight, is measured as the VGRF obtained from a force platform placed under both feet or a separate force platform placed under each foot. Two studies have reported weight-bearing asymmetry using the peak VGRF (7; 14). As demonstrated in Chapter 3, the peak VGRF is difficult to identify visually using the force trace in people with stroke and may not occur at the same time during the STS cycle compared with healthy adults. Therefore it may be beneficial to measure weight-bearing asymmetry at seat-off as identified by a VGRF of zero from a force platform under the chair.

The peak-to-peak COP displacement in the frontal and sagittal plane are the most common measures of balance during the STS task (7-10). These measures reflect the distance between the left and right most lateral positions or the most anterior and posterior positions from the start to the end of the STS cycle, respectively. People with stroke demonstrated greater COP displacement in the frontal plane, compared with healthy control participants suggesting balance impairment in this clinical population (7;8;10). No difference in sagittal plane COP displacement between people with stroke and healthy participants has been reported (7;8;10).

Balance is defined as the ability to maintain the position of the centre of mass (COM) relative to the base of support (BoS) and COP displacement reflects forces generated to maintain the COM position relative to the BoS (15). The peak-to-peak frontal and sagittal plane COP displacement provide global measures of balance during STS, however they do not inform the location of the COM or COP position relative to the affected or unaffected limb. Furthermore, it has been
suggested that the distance between the COP and COM provides a better measure of balance than the COM and COP displacement alone (16). However, no studies were found investigating the COP-COM distance during STS in people with stroke. Investigation of the frontal and sagittal plane COM and COP position relative to the affected or unaffected limb, and COM position relative to COP position in each plane at seat-off will further our knowledge of STS performance in people with stroke.

The purpose of this study was to compare temporal, weight-bearing and displacement measures of STS performance in people with stroke and healthy adults using traditional and novel measures of COM and COP displacement including position of COM and COP with respect to the midpoint between the medial malleoli in the frontal and sagittal plane at seat-off as well as the sagittal plane COP position of each limb with respect to the medial malleolus at seat-off.

5.2 Methods

5.2.1 Participants

People with stroke were recruited from the community, outpatient programs and from a list of participants who completed previous studies in the motor performance laboratory (MPL) who gave permission to be contacted for future studies. Healthy participants were recruited from the community and from a list of participants who completed previous studies in the MPL who gave permission to be contacted for future studies. Inclusion criteria for people with stroke were first known stroke, at least three months since stroke onset, only one side of the body affected by the stroke and the ability to rise from a chair without using their arms. Exclusion criteria included a known history of neurological impairment other than stroke affecting the lower limbs and lack of awareness of space on the affected side. Age (±5 years) and sex matched healthy participants were eligible to participate if they had no known neurological or orthopaedic condition affecting the lower extremities and no known balance or dizziness disorder. The university research ethics board approved the study protocol (Appendix A). Prior to providing informed consent (Appendix
B), the study procedures were explained and participants were given an opportunity to ask questions.

5.2.2 Instrumentation
Kinematic data were collected at 50Hz with an OPTOTRAK 3020 system (Northern Digital Inc, Waterloo, Canada) consisting of two arrays of optoelectronic motion tracking cameras. Three AMTI (AMTI, Newton, MA) force platforms (FPs) were used to gather kinetic data at 100Hz. One force platform (FP) was placed under the chair and one FP was placed under each foot. Alignment and registration of the cameras and FPs was conducted prior to each test session to reference the cameras and FPs to the same coordinate system for comparison of COP and COM measures.

5.2.3 Protocol
Participants visited the MPL once for testing STS performance. Demographic data were collected prior to the start of the test session to ensure participants met the inclusion criteria. Information regarding age, height, and weight were recorded for all participants. For participants with stroke, information regarding time since stroke onset and type of stroke was also recorded. In addition, participants with stroke completed a single letter cancellation test to screen for hemispatial neglect (Appendix C). For healthy participants, the dominant limb was determined as the limb participants would use to kick a soccer ball. Participants changed into shorts, a t-shirt and a pair of comfortable shoes for testing. Clusters of three or four infrared light emitting diodes (IREDs) mounted on rigid plastic molds were placed bilaterally on top of the foot, lateral mid-shank and lateral mid-thigh. Two additional IRED clusters were placed on the sacrum and at the 7th cervical vertebra. Bilateral marker clusters were secured with Velcro straps and reinforced with surgical tape to prevent movement of the clusters during testing. The sacrum cluster was secured with a strap and duct tape and the 7th cervical vertebra cluster was secured with surgical tape.
Subjects were seated on an armless, backless, height adjustable chair with each foot placed on a separate FP. Chair height was standardized to the height of each participant’s knee, measured as the length between the knee joint line and the floor. The minimum and maximum allowable chair height was 15 and 22 inches, respectively and adjustable using one-inch increments. The participant’s knee height was rounded up or down to the closest whole number to accommodate the one-inch increment adjustments on the chair. Participants sat with one third of their thigh length on the chair; thigh length was measured as the distance between the greater trochanter and the lateral knee joint line. Feet were placed in parallel with the medial border of the heels 10-15 cm apart. Knee angle in sitting was approximately 100 degrees of flexion. Participants were instructed to perform the STS task at a self-paced speed with their arms folded across their chest while looking at a target, to minimize head movement, placed on a wall 3.7 meters in front of them and 1.6 meters above the floor surface. Tape was placed on the FPs to promote consistency of foot placement between trials and stickers were placed on the chair and the participant’s thighs to promote consistency of seat position between trials. Participants performed one practice trial of the STS task followed by three trials used in the analysis. Three seconds of baseline data were collected at the beginning of each trial to provide a baseline measure of the vertical ground reaction force (VGRF) under the chair.

At the end of the STS trials, participants stood in view of both cameras for collection of a series of reference trials. A pointed probe with four IREDs was used to identify landmarks in relation to the IRED clusters. The four IREDs on the pointed probe were embedded in a fixed orientation to the tip of the probe. Landmarks identified bilaterally with the tip of the probe included the first and fifth metatarsal heads, lateral and medial malleoli, lateral and medial femoral epicondyles, greater trochanter, a point aligned vertically with each greater trochanter at the level of the anterior superior iliac spine and the acromion process of the scapula.
5.2.4 Definition of the STS cycle
The start of the STS cycle was defined as the first change in the VGRF under the chair from the baseline values. The end of the STS cycle was determined visually when the hip of the model created in Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD) reached full extension. Seat-off was defined as the first frame when the VGRF under the chair reached zero. This method for defining the STS cycle provides reliable measures of the total time and time for phase one and phase two as demonstrated in Chapter 4.

5.3 Outcome measures
The following temporal, weight-bearing and displacement measures of STS performance were chosen to compare our findings with those reported in previous studies and investigate if participants with stroke included in this study demonstrate similar differences in STS performance compared with healthy adults as reported in previous studies.

5.3.1 Temporal
1. Time to complete the STS cycle from start to end (Ttotal), in seconds.
2. Time to complete phase one of the STS cycle (Tp1), in seconds, from the start of the cycle to seat-off.
3. Time to complete phase two of the STS cycle (Tp2), in seconds, from seat-off to the end of the cycle.

5.3.2 Weight-bearing
4. Affected or non-dominant limb VGRF at seat-off (WB1), expressed as a percent of the total VGRF under the two feet at seat-off. Healthy adults perform the STS task with equal weight-bearing on the two limbs (12); we chose to compare weight-bearing of the non-dominant limb with the affected limb because we felt affected and non-dominant limb was the non-preferred limb in both groups.
5.3.3 Displacement

5.3.3.1 Frontal plane displacement
5 & 6. Medio-lateral center of pressure (MLCOP) and medio-lateral center of mass (MLCOM) displacement reported in centimeters. The peak-to-peak MLCOP and MLCOM displacement is defined as the distance between the most right and left lateral positions of the net COP (data from the two force platforms combined) and COM between the start and end of the STS cycle.

7. Distance between the net COP position and the midpoint between the medial malleoli in the frontal plane at seat-off (MLCOP_midline) reported in centimeters. Positive values reflect a COP position on the unaffected or dominant side of midline and negative values reflect a COP position on the affected or non-dominant side of midline.

8. Distance between the COM position and the midpoint between the medial malleoli in the frontal plane at seat-off (MLCOM_midline) reported in centimeters. Positive values reflect a COM position towards the unaffected or dominant side of midline and negative values reflect a COM position towards the affected or non-dominant side of midline at seat-off.

9. Distance between the COM and net COP position in the frontal plane at seat-off (MLCOM_COP), calculated for each trial, reported as the absolute value in centimeters. Note, when the COP and COM position were located on the same side of midline, one value was subtracted from the other value. When the COP and COM position were located on opposite sides of midline, the values were added to provide the distance between the two points. The average of three trials for each participant was used to calculate group data.

5.3.3.2 Sagittal plane displacement
10 & 11. Antero-posterior center of pressure (APCOP) and antero-posterior center of mass (APCOM) displacement reported in centimeters. The peak-to-peak APCOP and APCOM displacement is defined as the distance between the most anterior and posterior positions of the net COP and COM between the start and end of the STS cycle.
12. Distance between the net COP position and the midpoint between the medial malleoli in the sagittal plane at seat-off (APCOP_midpoint) reported in centimeters. Negative values reflect a COP position posterior to the midpoint and positive values reflect a COP position anterior to the midpoint.

13. Distance between the COM position and the midpoint between the medial malleoli in the sagittal plane at seat-off (APCOM_midpoint) reported in centimeters. Negative values reflect a COM position posterior to the midpoint and positive values reflect a COM position anterior to the midpoint.

14. Distance between the COM and net COP position at seat-off in the sagittal plane (APCOM_COP) reported as the absolute value in centimeters.

15. Distance between the COP position of the affected or non-dominant limb relative to the position of the respective medial malleolus at seat-off in the sagittal plane (APCOPa) reported in centimeters. Negative values reflect a COP position posterior to the malleolus and positive values reflect a COP position anterior to the malleolus.

16. Distance between the COP position of the unaffected or dominant limb relative to the position of the respective medial malleolus at seat-off in the sagittal plane (APCOPu) reported in centimeters. Negative values reflect a COP position posterior to the malleolus and positive values reflect a COP position anterior to the malleolus.

5.4 Data Processing and Analysis

Kinematic and kinetic data were filtered (lowpass, 6Hz Butterworth) and synchronized using Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD). An eight-segment model was created including bilateral foot, shank, and thigh, the pelvis and trunk. Segment lengths and joint centers were calculated based on the position of the landmarks (reference trials) in relation to the IRED clusters. A combined VGRF was calculated in C-Motion.
by adding the VGRF value from the FP under each foot. A net ML and AP COP path was also calculated in C-Motion using equation 1 (17).

Equation 1: \( \text{COP} = \text{COP1} \left( \frac{Fz1}{Fz1+Fz2} \right) + \text{COP2} \left( \frac{Fz2}{Fz1+Fz2} \right) \)

Where COP1 and COP2 are the COP obtained from each FP and the Fz1 and Fz2 are the VGRFs from the two FPs (17).

Synchronized kinematic and kinetic data were exported to Microsoft Excel (Microsoft Office 2002, Microsoft Corporation, USA) worksheets for further analysis.

All data in both groups, except MLCOP, APCOM_COP and APCOPa in people with stroke, were normally distributed as quantified with the Shapiro-Wilk test. For all measures with normal distribution, group means were calculated with the average of three trials from each individual and compared using a one-way analysis of variance (ANOVA), calculated using IBM SPSS Statistics (Version 20). We chose performed the analysis on all measures with an ANOVA due to the number of comparisons. A Mann-Whitney U test was used to compare group means for the three non-normally distributed measures. An alpha level of 0.05 was chosen for all comparisons. An alpha level of 0.05 may lead to a type one error, however this level was chosen because of the small sample size and the investigation of novel measures of STS performance.

5.5 Results

Due to instrumentation error, the COM measures, displacement measures relative to the frontal and sagittal midpoint between the malleoli and displacement measures relative to the medial malleolus were not calculated for one participant with stroke. Trial one data from a participant with stroke was excluded in the analysis due to difficulty identifying the start of the STS cycle. In this trial the participant temporarily sat back down on the chair after the initial lift-off of the buttocks from the chair. The mean value from the remaining two trials was used in the analysis.
5.5.1 Participants

Fifteen people with stroke and 15 age and sex matched healthy adults participated in the study. One participant with stroke had a knee joint replacement of the unaffected limb five years prior to the study and another participant with stroke wore an ankle foot orthosis. Examination of the scores from the participant with the knee joint replacement revealed values comparable to the group mean, therefore the data from this participant was included in the analysis. Examination of the scores from the participant who wore the ankle foot orthosis revealed values that were at the high or low end of the range of scores depending on the measure, for the group of participants with stroke. Due to the possibility of the data from this participant biasing the results toward a significant difference between groups, an analysis was performed with and without the data. Removing the data from this participant did not change the results for the comparison between groups ($p$ greater or less than 0.05), therefore the data from this participant was retained in the final analysis. Participant characteristics are presented in table 5.1. There were no differences in mean age, height and weight between the two groups ($p$>0.05). Mean values for all outcome measures are provided in table 5.2.

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<thead>
<tr>
<th>Table 5.1: Participant characteristics</th>
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<table>
<thead>
<tr>
<th></th>
<th>Stroke (n=15)</th>
<th>Healthy (n=15)</th>
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<td>Age(y)</td>
<td>66.69 ± 11.15</td>
<td>67.00 ± 10.90</td>
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<tr>
<td>Sex (M/F)</td>
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<tr>
<td>Mass (kg)</td>
<td>80.48 ± 13.24</td>
<td>73.49 ± 11.86</td>
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<tr>
<td>Height (m)</td>
<td>1.69 ± 0.07</td>
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<td>Affected or non-dominant foot (R/L)</td>
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<td>1/14</td>
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<tr>
<td>Time since stroke onset(y)</td>
<td>4.76 ± 8.48</td>
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### Table 5.2: Comparison of mean values in people with stroke and healthy adults

<table>
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<tr>
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<th>Stroke (n=15)</th>
<th>Healthy (n=15)</th>
<th>p value</th>
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<tr>
<td><strong>Ttotal (sec)</strong></td>
<td>2.99 ± .58</td>
<td>2.35 ± .34</td>
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<tr>
<td><strong>Tp1 (sec)</strong></td>
<td>1.20 ± .22</td>
<td>.95 ± .12</td>
<td>.001</td>
</tr>
<tr>
<td><strong>Tp2 (sec)</strong></td>
<td>1.79 ± .45</td>
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<td>.008</td>
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<tr>
<td><strong>WB1 (% total)</strong></td>
<td>44.77 ± 5.35</td>
<td>48.76 ± 2.42</td>
<td>.014</td>
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<tr>
<td><strong>MLCOP (cm)</strong></td>
<td>8.66 ± 4.97</td>
<td>4.69 ± 1.17</td>
<td>.010</td>
</tr>
<tr>
<td><strong>MLCOM (cm)</strong></td>
<td>2.58 ± .96*</td>
<td>1.76 ± .62</td>
<td>.011</td>
</tr>
<tr>
<td><strong>MLCOP_midline (cm)</strong></td>
<td>1.56 ± 1.85*</td>
<td>.11 ± .61</td>
<td>.008</td>
</tr>
<tr>
<td><strong>MLCOM_midline (cm)</strong></td>
<td>1.37 ± 1.82*</td>
<td>.24 ± .79</td>
<td>.036</td>
</tr>
<tr>
<td><strong>MLCOM_COP (cm)</strong></td>
<td>.68 ± .34*</td>
<td>.57 ± .30</td>
<td>.366</td>
</tr>
<tr>
<td><strong>APCOP (cm)</strong></td>
<td>9.29 ± 2.72</td>
<td>8.85 ± 1.65</td>
<td>.598</td>
</tr>
<tr>
<td><strong>APCOM (cm)</strong></td>
<td>25.80 ± 2.23*</td>
<td>27.56 ± 2.59</td>
<td>.062</td>
</tr>
<tr>
<td><strong>APCOP_midpoint (cm)</strong></td>
<td>.61 ± 2.19*</td>
<td>-.38 ± 1.23</td>
<td>.143</td>
</tr>
<tr>
<td><strong>APCOM_midpoint (cm)</strong></td>
<td>-7.52 ± 2.64*</td>
<td>-9.19 ± .80</td>
<td>.027</td>
</tr>
<tr>
<td><strong>APCOM_COP (cm)</strong></td>
<td>8.13 ± 2.13*</td>
<td>8.81 ± 1.57</td>
<td>.123</td>
</tr>
<tr>
<td><strong>APCOPa (cm)</strong></td>
<td>1.62 ± 4.86*</td>
<td>-1.11 ± 1.30</td>
<td>.112</td>
</tr>
<tr>
<td><strong>APCOPu (cm)</strong></td>
<td>-1.36 ± 1.83*</td>
<td>-1.43 ± 2.00</td>
<td>.915</td>
</tr>
</tbody>
</table>

*mean value of n=14

Abbreviations: Ttotal=total time, Tp1=time in phase one, Tp2=time in phase two, WB1=affected/non-dominant limb weight-bearing, MLCOP=peak-to-peak COP displacement in the frontal plane, MLCOM=peak-to-peak COM displacement in the frontal plane, MLCOP_midline=distance from midpoint between malleoli in the frontal plane, positive values=COP toward unaffected or dominant limb, MLCOM_midline=distance from midpoint between malleoli in the frontal plane; positive values=COM toward unaffected or dominant limb, MLCOM_COP=absolute distance between the COM and COP at seat-off in the frontal plane, APCOP=peak-to-peak COP displacement in the sagittal plane, APCOM=peak-to-peak COM displacement in the sagittal plane, APCOP_midpoint=distance between the COP position and the midpoint between the malleoli in the sagittal plane; positive values=COP anterior to midpoint, APCOM_midpoint=distance between the COM position and the midpoint between the malleoli in the sagittal plane; positive values=COM anterior to midpoint, APCOM_COP=absolute distance between the COM and COP position at seat-off in the sagittal plane, APCOPa=distance between the COP of the affected or non-dominant limb and the respective medial malleolus in the sagittal plane, positive values=COP anterior to malleoli, APCOPu=distance between the COP of the unaffected or dominant limb and the respective medial malleolus in the sagittal plane, positive values=COP anterior to malleoli.
5.5.2 Temporal measures

People with stroke required more time (2.99±0.58 seconds) to perform the STS task compared with healthy control participants (2.35±0.34 seconds) \( (F_{(1,28)}=13.78, \ p<0.01) \) (Table 5.2). The duration of phase one \( (F_{(1,28)}=14.92, \ p<0.01) \) and phase two \( (F_{(1,28)}=8.06, \ p<0.01) \) was greater in people with stroke.

5.5.3 Weight-bearing measures

The mean VGRF under the affected limb at seat-off, expressed as a percent of the total VGRF, was lower in people with stroke than the mean VGRF under the non-dominant limb of healthy control participants \( (F_{(1,28)}=6.92, \ p<0.05) \) (Table 5.2).

5.5.4 Frontal plane displacement

Total COP \( (F_{(1,28)}=9.09, \ p<0.01) \) and COM \( (F_{(1,27)}=7.56, \ p<0.05) \) displacement in the frontal plane over the duration of the STS task was greater in people with stroke than in healthy control participants (Table 5.2).

The mean COP position in the frontal plane at seat-off was further from midline in people with stroke \( (1.48±1.68 \text{ cm}) \) compared to healthy adults \( (.11±.61 \text{ cm}) \) \( (F_{(1,27)}=8.84, \ p<0.05) \). The mean COM position in the frontal plane at seat-off was further from the midline in people with stroke \( (1.37±1.82 \text{ cm}) \) compared to the COM position in the healthy control group \( (0.24±0.79 \text{ cm}) \) \( (F_{(1,27)}=4.87, \ p<0.05) \). Both the COP and COM were positioned towards the unaffected limb in people with stroke and the dominant limb in healthy adults.

Larger values of the mean distance between the COP and COM in the frontal plane at seat-off were observed in people with stroke, however the difference between groups did not reach statistical significance \( (F_{(1,27)}=2.72, \ p>0.05) \) (Table 5.2).
5.5.5 Sagittal plane displacement

The total COP displacement in the sagittal plane was approximately 9 cm and did not differ between groups. Although total displacement of the COM (APCOM) was lower in people with stroke (25.80±2.23cm) compared with healthy adults (27.56±2.59cm) the difference was not statistically significant ($F_{(1,27)}=3.78$, $p>0.05$) (Table 5.2).

There was no difference in the mean distance between the COP position and the midpoint between the malleoli in the sagittal plane at seat-off in people with stroke (0.61±2.19cm) and healthy adults (-0.38±1.23cm) ($p>0.05$).

At seat-off the COM was posterior to the malleoli in both groups and was significantly more posterior on average in the healthy adult group than in the group with stroke ($F_{(1,27)}=5.47$, $p<0.05$) (Table 5.2).

The distance between the COM and COP in the sagittal plane at seat-off did not differ between groups ($p>0.05$).

There was no difference between groups in the mean distance between the COP position of the affected or unaffected limb and non-dominant or dominant limb respectively, and the respective medial malleolus in the sagittal plane at seat-off.

5.6 Discussion

5.6.1 Temporal measures

Results demonstrated that people with stroke required more time to perform the STS task compared with healthy age and sex matched control participants. These findings are consistent with the results from previous studies (7;8;10;11). The time needed to perform the STS task reported in people with stroke ranged from 1.76 to 4.8 seconds and in healthy adults from 1.15 to 2.63 seconds (7;8;10;11). Values reported in our study fall within the range reported in the literature for both groups.
The greater amount of time needed to complete the STS task in people with stroke likely indicates greater difficulty performing the task, as reflected by time. Greater time to perform the STS task in people with stroke may also indicate that they use an alternate strategy due to muscle weakness of the affected limb or to maintain stability while performing the task by minimizing velocity of COM perturbation. When the STS cycle is divided into two phases, people with stroke required a longer time to complete each phase compared with healthy adults (Table 5.2). This finding demonstrates that people with stroke perform the entire movement more slowly than healthy adults and that the temporal difference is not specific to the first or second phase.

A post hoc within group comparison (paired t test) of time for phase one and phase two revealed a significant difference between the duration of each phase for both groups ($p<.05$). Both groups required a longer time to complete phase two, compared with phase one of the STS task (Table 5.2). Phase two is characterized by extension of the knee and hip to achieve upright standing with full body weight supported by the two feet. During phase two, participants must stabilize their COM within the second BoS and generate sufficient joint moments at the knee and hip to safely and successfully complete the STS task.

### 5.6.2 Weight-bearing measures

Results from this study demonstrated less weight-bearing on the affected limb in people with stroke compared with the non-dominant limb in healthy adults during STS (Table 5.2). Our results are consistent with findings from previous studies that demonstrated weight-bearing asymmetry when performing the STS task with less weight placed on the affected limb compared with the unaffected limb in people with stroke (7;12;13;14). The mean weight-bearing of the affected limb reported in this study was $44.77\pm5.35\%$, a value close to equal weight-bearing between both limbs. A post hoc comparison revealed that this value was different from 50%, or equal weight-bearing between limbs ($t_{28}=-3.78, p<0.05$). The reported value however, suggests a high level of function among the participants with stroke in this study. Functional measures
were not included, however all participants with stroke were able to walk into the MPL, ascend/descend stairs and perform the STS task without using their arms supporting the high level of function in the participants with stroke.

Decreased affected limb weight-bearing in people with stroke may be the result of the neurological sequelae following a stroke including sensory and muscle impairments or learned non-use of the affected limb. Impaired sensation, including proprioception, following a stroke may contribute to decreased loading of the affected limb and decreased confidence in placing an equal amount of weight through the limb. Muscle weakness following a stroke may also contribute to decreased affected limb weight-bearing due to an inability to generate net muscle moments equal to the unaffected limb.

Another possible reason for decreased loading of the affected limb is learned non-use (18). Loading of the affected limb may be avoided in the early stages (less than six months) of recovery following stroke due to impaired sensation, muscle weakness and failed attempts of using the limb (18). During this time, compensatory patterns may be used to accomplish the STS task. If the compensatory patterns persist into the post-acute phase (greater than six months) following a stroke, a learned non-use phenomenon may occur despite having the ability to weight-bear equally through both limbs during STS (18;19).

5.6.3 Frontal plane displacement
People with stroke demonstrated greater peak-to-peak ML COP displacement compared with healthy control participants when performing the STS task (Table 5.2). This finding is consistent with that of previous studies with higher values of ML COP displacement suggesting balance impairment when performing the STS task. Values of peak-to-peak ML COP displacement in people with stroke were reported between 7.5±2.5cm (9) and 21.05±9.91cm (7). The range of values reported in people with stroke may reflect stroke severity. For example, Cheng et al. (7) reported a mean ML COP displacement of 12.05±6.0 and 21.05±9.91cm in a group of people
with stroke who reported no falls and a group who reported at least one fall since stroke onset, respectively.

People with stroke also demonstrated greater peak-to-peak ML COM displacement compared with healthy control participants during the STS task (Table 5.2). This finding is consistent with Hesse et al. (20) who reported a larger ML COM displacement in people with stroke before (p<0.001) and after seat-off (p<0.002). Hesse et al. (20) reported a mean ML COM displacement of 1.6±1.4% of height and 1.8±1.5% of height before and after seat-off respectively, in people with stroke. The peak-to-peak ML COM displacement in people with stroke in the present study was 1.5±0.57% of height and is comparable with values reported by Hesse et al. (20).

Balance is the ability to maintain the position of the COM relative to the BoS and the COP displacement reflects forces generated to maintain the COM position within the BoS (15). Muscles responsible for balance control in the frontal plane include the hip abductors and adductors (17). The larger ML COM displacement suggests decreased balance in people with stroke and the larger ML COP displacement suggests impaired balance control mechanisms in the frontal plane. The larger ML COM and ML COP displacement suggest that rehabilitation include exercises to increase hip abductor and adductor strength and exercises that challenge balance in the frontal plane to improve balance during STS.

The peak-to-peak ML COP and COM displacement provide global measures of balance in the frontal plane, however these measures do not illustrate the position of the COP or COM displacement with respect to the midline. One novel measure of STS performance investigated in this study was the position of the COP and COM with respect to the midline in the frontal plane at the critical point of seat-off.

People with stroke demonstrated a COP and COM position further away from midline towards the unaffected limb in the frontal plane at seat-off compared to healthy adults (Table 5.2). One possible explanation for these results is the reported finding of increased weight-bearing of the unaffected limb. Increased weight-bearing of the unaffected limb may be due to lack of
confidence placing equal weight through the affected limb because of impaired sensation and muscle weakness following a stroke. Conversely, a greater amount of weight through the unaffected limb may reflect greater confidence placing the COM over the limb, thereby resulting in a shift of the COP and COM away from midline toward the unaffected limb.

The final measure of frontal plane balance in this study is the distance between the COM and COP at seat-off. The COP position varies with movement of the COM to maintain the COM relative to the BoS and it has been suggested that the distance between the COM and COP (COP-COM) provides better insight into postural control mechanisms than the COM or COP position alone (16;21). Termoz et al. (22) reported a larger mean frontal plane COP-COM distance in older adults compared to younger adults in standing (p<0.05) and this was attributed to postural impairment. In the present study a difference in this measure between people with stroke and healthy adults was not observed suggesting that this measure does not illustrate balance impairment in people with stroke. Two possible reasons for not observing a difference between groups was the large variability observed in people with stroke and the high level of physical functioning of the group of people with stroke. Most of the participants were able to perform the STS task with ease; a group with a lower level of function demonstrating difficulty performing the STS task may have demonstrated a difference in MLCOM_COP.

5.6.4 Sagittal plane displacement
Findings from this study demonstrated no difference in the peak-to-peak AP COP and AP COM displacement in people with stroke compared with healthy age and sex matched adults (Table 5.2). All participants performed the STS task from a standardized position with the feet placed at the same distance from the anterior edge of the seat and one third of the participant’s thigh length placed on the chair. The standardized foot and thigh position, and setting of chair height to shank length likely minimized differences between groups in sagittal plane movement of the COP and COM, respectively.
No difference in AP COP displacement in people with stroke compared with healthy adults was reported in previous studies (7;8;10). Mean AP COP displacement in people with stroke reported in the literature ranged from 7.2±1.19cm (10) to 10.23±3.35cm (7) and from 8.18±2.1cm (10) to 8.6±2.1cm (7) in healthy adults. Findings from the present study are consistent with values presented in previous studies. As a global measure of balance in the sagittal plane, peak-to-peak COP and COM displacement did not illustrate differences in STS performance in people with stroke compared with healthy age and sex matched adults using a standardized protocol.

In this study we investigated the position of the COP and COM with respect to the position of the malleoli in the sagittal plane. The findings demonstrated no difference in COP positioning at seat-off in people with stroke compared with healthy adults. In contrast, the COM position was further forward in the sagittal plane at seat-off in people with stroke compared with healthy adults. People with stroke performed the STS task more slowly than their age matched peers (Table 5.2) and their peak sagittal plane COM velocity was smaller than their age matched peers without stroke (p<0.05) (data not reported). The slower speed of movement may lead to a more anterior COM position at seat-off to compensate for lower momentum. Inkster et al. (23) reported a mean COM displacement that was larger and more anterior in people with Parkinson’s disease (PD) between the start of the STS cycle and seat-off compared with age and sex matched healthy adults. Inkster et al. (23) also reported an earlier peak hip flexion angle in people with PD during the STS task, task resulting in a more forward COM position at seat-off. This may reflect a strategy to compensate for impaired balance and decreased muscle strength by increasing the amount of time that the COM stays within the second BoS (23). In a second study Mourey et al. (24) reported a more posterior mean COM position in older adults compared with younger adults at the critical point of seat-off during STS. It was suggested that the more posterior COM position in older adults was a strategy used to minimize the risk of falling forward when standing-up from sitting. The more anterior COM position at seat-off in people with stroke, reported in the present study, is consistent with findings reported by Inkster et al. (23), which may suggest a
strategy to compensate for decreased muscle strength (25-27). It may also indicate a compensation for impaired balance by minimizing the number of postural corrections required to stabilize the COM within the new BoS following seat-off.

Findings from this study demonstrated no difference in the distance between the COP and COM in the sagittal plane in people with stroke compared with healthy adults. The distance between the COP and COM has been described as a measure of the efficacy of balance control (16; 21). Findings from the present study suggest that this measure as well as peak-to-peak COP and COM displacement do not illustrate differences in sagittal plane balance control in people with stroke compared with healthy adults.

People with stroke demonstrate weight-bearing asymmetry during STS (7;12-14). Therefore, we investigated the COP position of the affected and unaffected limb in people with stroke with respect to the position of the medial malleolus of the respective foot, in the sagittal plane. No difference was found in COP position under the affected or unaffected limb in people with stroke compared with the non-dominant or dominant limb in healthy adults, respectively. Although a difference in APCOPa was not observed between groups, a large between subject variability was observed in people with stroke as demonstrated by the large standard deviation of the group mean. The values for this measure in people with stroke ranged from -2.75cm to 15.17cm. The largest value, 15.17cm was observed in the participant who wore the ankle foot orthosis, which likely impacted the position of the COP under the affected foot. Measures of sensation, muscle strength and muscle tone were not collected in this study. Further investigation of the role of these possible impairments on sagittal plane STS performance is warranted.

5.7 Conclusions

Findings from this study demonstrated that people with stroke required more time to complete the STS task and had more weight on the unaffected limb at seat-off compared with healthy age and sex matched adults. Greater peak-to-peak COP and COM displacement in the frontal plane
suggests balance impairment in people with stroke and highlights a need to address muscle strength of the hip abductors and adductors and balance training in this plane. Findings from this study also demonstrated positioning of the COM towards the unaffected limb at seat-off in people with stroke, which may by the result of increased weight-bearing of the unaffected limb. The COM position in the sagittal plane at seat-off demonstrated a difference in STS performance in people with stroke and highlights a potential need to improve strength of the affected limb and sagittal plane balance.

5.8 References


Chapter 6

The effect of lower limb constraint-induced movement strategies on sit-to-stand performance in people with stroke

6.1 Introduction
Performance of the sit-to-stand (STS) task in people with stroke is characterized by weight-bearing asymmetry (1-4) with a greater amount of weight placed on the unaffected limb and impaired balance as evidenced by a larger medio-lateral (ML) centre of pressure (COP) (2;4;5) displacement than seen in age matched healthy adults. Consequently, improved weight-bearing symmetry and balance during STS are goals of rehabilitation in this population. One treatment strategy for achieving these goals is constraint-induced movement therapy (CIMT). CIMT promotes affected limb weight-bearing by placing the unaffected limb in a position of biomechanical disadvantage, thereby promoting use of the affected limb when performing the STS task (1;6;7). Constraint-induced movement (CIM) strategies for the lower limb during STS include placement of the unaffected limb ahead of the affected limb (1;3;6-10) and placement of the unaffected limb on a solid (8) or compliant (foam) block (1) while performing sit-to-stand (STS) task.
Investigation of the effect of CIM strategies for the lower limb has focused on changes to weight-bearing symmetry and joint moment symmetry with little investigation of changes to balance in the frontal and sagittal planes. Studies investigating changes to STS performance with the unaffected limb placed half a foot length ahead of the affected limb found a decrease in weight-bearing asymmetry (1;3;6;8) as well as reduced joint moment asymmetry (3;7) at the hip and knee compared with STS performance with the feet placed in parallel. Rocha et al. (8) found less weight-bearing asymmetry in people with stroke during STS when the unaffected limb was placed on a solid block equal to 25% of the seat height. Conversely, Brunt et al. (1) reported no
change in weight-bearing symmetry when the unaffected limb was placed on a compliant block equal to 25% of the chair height.

In addition to weight-bearing asymmetry, people with stroke demonstrate impaired balance in the frontal plane when performing the STS task (2;4;5). Only one study was found that investigated frontal plane balance during STS with a CIM strategy (9). The authors reported a smaller ML COP displacement in people with stroke when they performed the STS task with the unaffected limb placed half a foot length ahead of the affected limb, compared with STS with the feet placed in parallel (9).

People with stroke have a higher risk of falling than their age matched peers with most falls occurring during transition movements including the STS task (11). Weight-bearing asymmetry and impaired balance are two potential risk factors for falls during STS in people with stroke (2). CIMT is a rehabilitation strategy for improving weight-bearing symmetry and balance during STS, however only one study investigated the effect of CIM strategies on frontal plane balance during STS (9). In addition, only one asymmetrical foot position, one solid block height and one compliant block density have been investigated. Rising to stand from sitting is a more complex task than walking (12) and over 50% of people with stroke will have hemiparesis of the affected side of the body (13). Consequently, people with stroke may find it difficult to perform the STS task with the CIM parameters outlined in the literature. The effect of placing the unaffected limb only a quarter of a foot length ahead of the affected limb or placement of the unaffected limb on a block height less than 25% of the chair height on STS performance in people with stroke remains unknown.

The purpose of this study was to investigate the effect of several CIM strategies for the lower limb on temporal, weight-bearing and displacement measures of STS performance in people with stroke.
6.2 Methods

6.2.1 Participants
People with stroke were recruited from the community, outpatient programs and from a list of participants who completed previous studies in the Motor Performance Laboratory (MPL) who gave permission to be contacted for future studies. Participants were included if it was their first known stroke, if it was at least six months since stroke onset, if only one side of the body was affected by the stroke and if they were able to rise from a chair without using their arms. Exclusion criteria included a known history of neurological impairment other than stroke affecting the lower limbs and lack of awareness of space on the affected side. The university research ethics board approved the study protocol (Appendix A). Prior to participation, the study procedures were explained and participants were given an opportunity to ask questions before providing informed consent. All participants provided informed consent (Appendix B).

6.2.2 Instrumentation
Kinematic data were collected at 50Hz with an OPTOTRAK 3020 system (Northern Digital Inc, Waterloo, Canada) consisting of two arrays of optoelectronic motion tracking cameras. Three AMTI (AMTI, Newton, MA) force platforms (FPs) were used to gather kinetic data with a sampling frequency of 100Hz. One force platform (FP) was placed under the chair and one FP was placed under each foot. Alignment and registration of the cameras and FPs was conducted prior to each test session to reference the cameras and FPs to the same coordinate system to allow determination of the center of mass (COM) with respect to the centre of pressure (COP).

6.2.3 Protocol
Participants visited the MPL once for testing STS performance. History and demographic data were collected prior to the start of the test session for descriptive purposes and to ensure participants met the inclusion criteria. Information regarding each participant’s age, height,
weight, time since stroke onset and type of stroke was recorded. Participants also completed a single letter cancellation test to screen for hemispatial neglect (Appendix C).

Participants changed into shorts, a t-shirt and a pair of comfortable shoes for testing. Clusters of three or four infrared light emitting diodes (IREDs) mounted on rigid plastic molds were placed bilaterally on top of the foot, lateral mid-shank and lateral mid-thigh. Two additional IRED clusters were placed on the sacrum and at the 7th cervical vertebra. Bilateral marker clusters were secured with Velcro straps and reinforced with surgical tape to prevent movement of the clusters during testing. The sacrum cluster was secured with a strap and duct tape and the 7th cervical vertebra cluster was secured with surgical tape.

Participants were asked to perform a series of STS trials from an armless, backless, height adjustable chair with each foot placed on a separate FP. Chair height was standardized to the height of each participant’s knee, measured as the length between the knee joint line and the floor. The minimum and maximum allowable chair height was 15 and 22 inches, respectively and adjustable using one-inch increments. The participant’s knee height was rounded up or down to the closest whole number to accommodate the one-inch increment adjustments on the chair. Participants sat with one third of their thigh length on the chair; thigh length was measured as the distance between the greater trochanter and the lateral knee joint line.

Participants performed the STS task with no added CIM condition and using three CIM strategies including four solid block conditions, two compliant (foam) block conditions and two asymmetrical foot positions. Baseline trials were performed with the feet placed in parallel, with the medial border of the heels 10-15cm apart; bilateral knee angle in sitting was approximately 100 degrees of flexion. Four solid block (SB) heights were tested, 2.54 (SB1), 5.08 (SB2), 7.62 (SB3) and 10.16cm (SB4), with the unaffected foot placed on the solid block and in parallel with the affected foot. Two compliant block (CB) densities were tested, 2.72 (CB1) and 6.63kg (CB2), with the unaffected foot placed on the compliant block and in parallel with the affected foot. The compliant blocks were constructed from rebond foam and were 10.16cm in height. Two
asymmetrical foot positions were tested with the unaffected foot placed a quarter (*quart*) or a half (*half*) a foot length ahead of the affected foot. For all conditions, distance between the medial border of the heels in the frontal plane was 10-15cm. Participants performed three baseline STS trials and three consecutive trials of each condition. Baseline trials were always performed first followed by random presentation of each CIM strategy. These strategies were chosen because they have been shown to affect weight-bearing symmetry in previous studies and to allow comparison to these studies (1;6;8). Multiple levels of the solid block and asymmetrical foot conditions were chosen to determine if the effect of the strategy was consistent across each level. Two compliant block densities were chosen to investigate the effect of varying compliance on STS performance.

Randomization was performed prior to each test session by pulling pieces of paper with the name of one condition (*SB1, SB2, SB3, SB4, CB1, CB2, quart or half*) out of a hat and recording the condition on a protocol sheet with eight consecutive spaces. Conditions were recorded in the order pulled out of the bag; however, to minimize possible carry-over effects between conditions, two solid block, compliant block or asymmetrical foot conditions were not presented consecutively. For example, if the SB3 condition was pulled out of the hat immediately following the SB1 condition, it was recorded in the second space following the SB1 condition; the space following the SB1 condition was filled with the first compliant block or asymmetrical foot condition pulled from the hat.

Participants were instructed to perform the STS task at a self-paced speed with their arms folded across their chest while looking at a target located 3.7 meters in front of the chair and 1.6 meters above the floor surface. Tape was placed on the FPs to promote consistency of foot placement between trials and stickers were placed on the chair and the participant’s thighs to promote consistency of seat position between trials. For all conditions, participants performed one practice trial of the STS task followed by three trials for analysis. Three seconds of quiet sitting
were collected at the beginning of each trial to provide a baseline measure of the vertical ground reaction force (VGRF) on the chair.

At the end of the STS trials, participants stood in view of both cameras for collection of a series of reference trials. A pointed probe with four IREDs embedded in a fixed orientation to the tip of the probe was used to identify landmarks in relation to the IRED clusters. Landmarks identified bilaterally with the tip of the probe included the first and fifth metatarsal heads, lateral and medial malleoli, lateral and medial femoral epicondyles, greater trochanter, a point aligned vertically with each greater trochanter at the level of the anterior superior iliac spine and the acromion process of the scapula.

6.2.4 Definition of the STS cycle
The start of the STS cycle was defined as the first change in the VGRF under the chair from the baseline values. The end of the STS cycle was determined visually when the hip of the model created in Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD) reached full extension. Seat-off was defined as the first frame when the VGRF under the chair reached zero.

6.3 Outcome measures
The following temporal, weight-bearing and displacement measures of STS performance were included in this study to provide a comprehensive analysis of changes to STS performance with the strategies with a specific focus on measures of balance.

6.3.1 Temporal measures
1. Time to complete the cycle from start to end (T_total), in seconds.
2. Time to complete phase one (T_p1), in seconds, from the start of the STS cycle to seat-off.
3. Time to complete phase two (T_p2), in seconds, from seat-off to the end of the STS cycle.
6.3.2 Weight-bearing measures

4. Affected limb VGRF at seat-off (WB), expressed as a percent of the total VGRF under the two feet at seat-off.

6.3.3 Displacement

6.3.3.1 Frontal plane displacement
5 & 6. Medio-lateral center of pressure (MLCOP) and medio-lateral center of mass (MLCOM) displacement reported in centimeters. The peak-to-peak MLCOP and MLCOM displacement was defined as the distance between the most right and left lateral positions of the net COP (data from the two force platforms combined) and COM in the frontal plane between the start and end of the STS cycle.

7. Distance between the net COP position and the midpoint between the medial malleoli in the frontal plane at seat-off (MLCOP_midline) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. The midpoint for each condition was calculated using the position of the malleoli relative to the foot and shank IRED cluster obtained in C-Motion. Positive values reflect a COP position toward the unaffected side of midline and negative values reflect a COP position toward the affected side of midline.

8. Distance between the COM position and the midpoint between the medial malleoli in the frontal plane at seat-off (MLCOM_midline) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. The midpoint for each condition was calculated using the position of the malleoli relative to the foot and shank IRED cluster obtained in C-Motion. Positive values reflect a COM position toward the unaffected side of midline and negative values reflect a COM position toward the affected side of midline at seat-off.
9. Distance between the COM and net COP position in the frontal plane at seat-off (MLCOM_COP), calculated for each trial, reported as an absolute value in centimeters. Note, when the COP and COM position were located on the same side of midline, one value was subtracted from the other value. When the COP and COM position were located on opposite sides of midline, the values were added. The average of three trials for each participant was used to calculate group data.

6.3.3.2 Sagittal plane displacement

10 & 11. Antero-posterior (AP) center of pressure (APCOP) and antero-posterior center of mass (APCOM) displacement reported in centimeters. The peak-to-peak APCOP and APCOM displacement was defined as the distance between the most anterior and posterior positions of the net COP and COM in the sagittal plane between the start and end of the STS cycle.

12. Distance between the net COP position and the midpoint between the medial malleoli in the sagittal plane at seat-off (APCOP_midpoint) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. The midpoint for each condition was calculated using the position of the malleoli relative to the foot and shank IRED cluster obtained in C-Motion. Positive values reflect a COP position anterior to the midpoint and negative values reflect a COP position posterior to the midpoint.

13. Distance between the COM position and the midpoint between the medial malleoli in the sagittal plane at seat-off (APCOM_midpoint) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. The midpoint for each condition was calculated using the position of the malleoli relative to the foot and shank IRED cluster obtained in C-Motion. Positive values reflect a COM position anterior to the midpoint and negative values reflect a COM position posterior to the midpoint.
14. Distance between the COM and net COP position at seat-off in the sagittal plane (APCOM_COP) reported as the absolute value in centimeters.

15. Distance between the COP position of the affected limb relative to the position of the affected limb medial malleolus at seat-off in the sagittal plane (APCOPa) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. Positive values reflect a COP position anterior to the malleolus and negative values reflect a COP position posterior to the malleolus.

16. Distance between the COP position of the unaffected limb relative to the position of the unaffected limb medial malleolus at seat-off in the sagittal plane (APCOPu) reported in centimeters. The position of the medial malleoli relative to the IRED cluster on the foot and shank was determined with the pointed probe in the reference trials following the end of the STS trials. Positive values reflect a COP position anterior to the malleolus and negative values reflect a COP position posterior to the malleolus.

6.4 Data Processing and Analysis

Kinematic and kinetic data were filtered (lowpass, 6Hz Butterworth) and synchronized using Visual 3D motion analysis software (Visual 3D, C-Motion Inc., Germantown, MD). An eight-segment model was created including bilateral foot, shank, and thigh, the pelvis and trunk. Segment lengths and joint centers were calculated based on the position of the landmarks (reference trials) in relation to the IRED clusters. A combined VGRF was calculated in C-Motion by adding the VGRF value from the FP under each foot. A net ML and AP COP path was also calculated in C-Motion using an equation from Winter (14), (Equation 1). Synchronized kinematic and kinetic data were exported to Microsoft Excel (Microsoft Office 2002, Microsoft Corporation, USA) worksheets for further analysis.
Equation 1: \( \text{COP} = \text{COP}1 \left( \frac{Fz1}{Fz2+Fz1} \right) + \text{COP}2 \left( \frac{Fz2}{Fz1+Fz2} \right) \)

Where COP1 and COP2 are the COP obtained from each FP and the Fz1 and Fz2 are the VGRFs from the two FPs (14)

Descriptive statistics (mean and one standard deviation) were calculated for each variable across all conditions using the average of three trials from each individual. Results for each dependent variable were tested with a repeated measures analysis of variance (ANOVA) calculated using IBM SPSS Statistics (version 20). An alpha level of 0.05 was chosen for all comparisons. All results were examined for violation of sphericity, determined by a significant value for Mauchly’s test of sphericity. The Greenhouse-Geisser correction was used to determine significance when sphericity was violated. When a main effect of condition was found, a pairwise comparison was performed to determine the source of the main effect.

6.5 Results

Due to instrumentation error, COM measures, displacement measures relative to the frontal and sagittal midpoint between the malleoli and displacement measures relative to the medial malleolus were not calculated for one participant with stroke. Trial one data from a participant with stroke were excluded in the analysis due to difficulty identifying the start of the STS cycle. In this trial the participant temporarily sat back down on the chair after the initial lift-off of the buttocks from the chair. The mean value from the remaining two trials was used in the analysis. Thirteen participants were able to perform the STS task across all conditions. One participant was only able to perform the STS task with the baseline and 1inch solid block conditions. A second participant was able to perform the STS task with the baseline, 1inch, 2inch solid blocks and the quart-foot conditions. Statistical analysis was carried out on the 13 participants who were able to perform the STS task across all conditions. Statistical analysis for COM measures was carried out on 12 participants due to instrumentation error for one participant.
The assumption of sphericity was violated for the following measures: Ttotal, Tp1, Tp2, MLCOP, MLCOM, APCOP, APCOM, APCOP_midpoint, APCOPa, APCOPu. For all of these measures, the Greenhouse-Geisser correction was used to determine a main effect of condition.

6.5.1 Participants

Fifteen people with stroke participated in the study. One participant, (CVA7) wore an ankle foot orthosis and another participant (CVA6) had a knee joint replacement of the unaffected limb five years prior to the study. Participant characteristics are presented in table 6.1. Mean values for all outcome measures across all conditions are provided in table 6.2.
## Table 6.1: Participant Characteristics

<table>
<thead>
<tr>
<th>Participant</th>
<th>Age (y)</th>
<th>Sex</th>
<th>Weight (kg)</th>
<th>Affected limb</th>
<th>Time since stroke onset (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA1</td>
<td>68</td>
<td>M</td>
<td>94</td>
<td>R</td>
<td>41</td>
</tr>
<tr>
<td>CVA2</td>
<td>55</td>
<td>M</td>
<td>85</td>
<td>R</td>
<td>40</td>
</tr>
<tr>
<td>CVA3</td>
<td>64</td>
<td>M</td>
<td>78</td>
<td>L</td>
<td>132</td>
</tr>
<tr>
<td>CVA4</td>
<td>52</td>
<td>M</td>
<td>84</td>
<td>L</td>
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<tr>
<td>CVA5</td>
<td>46</td>
<td>M</td>
<td>85</td>
<td>R</td>
<td>23</td>
</tr>
<tr>
<td>CVA6*</td>
<td>72</td>
<td>M</td>
<td>82</td>
<td>R</td>
<td>16</td>
</tr>
<tr>
<td>CVA7**</td>
<td>64</td>
<td>F</td>
<td>70</td>
<td>R</td>
<td>408</td>
</tr>
<tr>
<td>CVA8</td>
<td>66</td>
<td>M</td>
<td>98</td>
<td>L</td>
<td>20</td>
</tr>
<tr>
<td>CVA9*</td>
<td>59</td>
<td>M</td>
<td>50</td>
<td>L</td>
<td>18</td>
</tr>
<tr>
<td>CVA10</td>
<td>62</td>
<td>M</td>
<td>101</td>
<td>R</td>
<td>7</td>
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<tr>
<td>CVA11</td>
<td>77</td>
<td>F</td>
<td>88</td>
<td>R</td>
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<td>CVA12</td>
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<td>M</td>
<td>82</td>
<td>R</td>
<td>25</td>
</tr>
<tr>
<td>CVA13</td>
<td>80</td>
<td>F</td>
<td>69</td>
<td>L</td>
<td>53</td>
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<tr>
<td>CVA14</td>
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<tr>
<td>CVA15</td>
<td>80</td>
<td>F</td>
<td>76</td>
<td>R</td>
<td>24</td>
</tr>
</tbody>
</table>

Abbreviations: y=years, M=male, F=female, kg=kilograms, R=right, L=left, m=months, *=participant unable to complete sit-to-stand with all conditions, therefore data were not included in the analysis, τ=participant with a knee joint replacement, π=participant wore an ankle foot orthosis.
### Table 6.2: Mean (SD) of all measures across all conditions

<table>
<thead>
<tr>
<th>Measure</th>
<th>Baseline</th>
<th>SB1</th>
<th>SB2</th>
<th>SB3</th>
<th>SB4</th>
<th>CB1</th>
<th>CB2</th>
<th>Quart</th>
<th>Half</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ttotal (sec)</td>
<td>2.92(.57)</td>
<td>2.92(.56)</td>
<td>2.92(.56)</td>
<td>2.90(.49)</td>
<td>2.95(.51)</td>
<td>3.01(.57)</td>
<td>3.04(.58)</td>
<td>3.09(.55)</td>
<td>3.13(.66)</td>
</tr>
<tr>
<td>WB (% total)</td>
<td>45.78(4.95)</td>
<td>48.38(6.48)</td>
<td>49.54(5.63)</td>
<td>49.93(6.07)</td>
<td>51.59(5.85)</td>
<td>51.00(6.79)</td>
<td>50.72(6.91)</td>
<td>49.92(7.01)</td>
<td>55.13(7.15)</td>
</tr>
<tr>
<td>MLCOP (cm)</td>
<td>7.36(3.89)</td>
<td>5.64(1.53)</td>
<td>6.09(2.83)</td>
<td>6.70(3.22)</td>
<td>7.37(3.89)</td>
<td>7.20(3.15)</td>
<td>6.66(3.03)</td>
<td>7.04(2.06)</td>
<td>8.55(2.24)</td>
</tr>
<tr>
<td>MLCOM (cm)*</td>
<td>2.35(.78)</td>
<td>2.41(1.01)</td>
<td>2.83(.79)</td>
<td>2.65(1.04)</td>
<td>3.14(1.42)</td>
<td>3.06(.93)</td>
<td>3.03(1.23)</td>
<td>2.72(.90)</td>
<td>2.95(1.31)</td>
</tr>
<tr>
<td>MLCOP_mid (cm)*</td>
<td>1.00(1.27)</td>
<td>.39(1.56)</td>
<td>.34(1.33)</td>
<td>.31(1.38)</td>
<td>.02(1.48)</td>
<td>.16(1.53)</td>
<td>.25(1.68)</td>
<td>-2.22(1.77)</td>
<td>-1.75(1.70)</td>
</tr>
<tr>
<td>MLCOM_mid (cm)*</td>
<td>.79(1.12)</td>
<td>.30(1.16)</td>
<td>.43(1.26)</td>
<td>.13(1.10)</td>
<td>.01(1.09)</td>
<td>.26(1.31)</td>
<td>.23(1.25)</td>
<td>-1.0(1.09)</td>
<td>-1.19(1.15)</td>
</tr>
<tr>
<td>MLCOM_COP (cm)*</td>
<td>.60(2.29)</td>
<td>.74(4.2)</td>
<td>.74(6.2)</td>
<td>.72(4.3)</td>
<td>.68(4.7)</td>
<td>.77(5.3)</td>
<td>.71(5.6)</td>
<td>.79(6.0)</td>
<td>.95(5.7)</td>
</tr>
<tr>
<td>APCOP (cm)</td>
<td>8.70(2.37)</td>
<td>8.60(2.22)</td>
<td>9.85(5.22)</td>
<td>8.29(1.97)</td>
<td>8.67(1.95)</td>
<td>7.70(1.78)</td>
<td>8.60(1.70)</td>
<td>9.41(2.35)</td>
<td>10.49(2.68)</td>
</tr>
<tr>
<td>APCOM (cm)*</td>
<td>25.39(2.05)</td>
<td>26.06(2.67)</td>
<td>26.15(2.78)</td>
<td>26.12(2.21)</td>
<td>25.71(3.34)</td>
<td>26.88(2.54)</td>
<td>26.67(2.39)</td>
<td>29.33(3.33)</td>
<td>32.45(3.98)</td>
</tr>
<tr>
<td>APCOP_mid (cm)*</td>
<td>.53(2.24)</td>
<td>.57(2.22)</td>
<td>.36(2.94)</td>
<td>1.06(2.61)</td>
<td>.80(2.60)</td>
<td>1.85(2.17)</td>
<td>1.57(2.35)</td>
<td>-2.21(2.42)</td>
<td>-9.4(2.95)</td>
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<tr>
<td>APCOM_mid (cm)*</td>
<td>-7.30(2.73)</td>
<td>-7.11(2.88)</td>
<td>-6.94(2.83)</td>
<td>-7.49(3.00)</td>
<td>-7.37(2.90)</td>
<td>-6.53(2.95)</td>
<td>-6.15(3.28)</td>
<td>-8.59(2.74)</td>
<td>-10.35(3.53)</td>
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<tr>
<td>APCOM_COP (cm)*</td>
<td>7.83(1.58)</td>
<td>7.68(1.69)</td>
<td>7.30(2.07)</td>
<td>8.54(1.82)</td>
<td>8.17(1.72)</td>
<td>8.37(1.35)</td>
<td>7.72(1.70)</td>
<td>8.37(1.60)</td>
<td>9.41(1.74)</td>
</tr>
<tr>
<td>APCOPa (cm)*</td>
<td>.85(2.96)</td>
<td>1.49(4.49)</td>
<td>.40(2.96)</td>
<td>.41(3.04)</td>
<td>.24(3.30)</td>
<td>.50(3.04)</td>
<td>.39(3.22)</td>
<td>.85(3.10)</td>
<td>.74(3.12)</td>
</tr>
<tr>
<td>APCOPu (cm)*</td>
<td>-1.40(1.96)</td>
<td>-1.21(2.10)</td>
<td>-1.57(3.03)</td>
<td>.21(3.31)</td>
<td>-.26(2.21)</td>
<td>1.57(1.61)</td>
<td>1.04(1.91)</td>
<td>-2.86(1.48)</td>
<td>-3.18(1.43)</td>
</tr>
</tbody>
</table>

n=13,*n=12

Abbreviations: Total=total time to complete the STS cycle, WB=affected limb weight-bearing at seat-off, MLCOP and MLCOM=peak-to-peak COP and COM displacement in the frontal plane, respectively, MLCOP_mid and MLCOM_mid=distance between the COP and COM position and the midline between the malleoli in the frontal plane at seat-off, respectively; positive and negative values reflect a position toward the unaffected and affected limb relative to midline, respectively, MLCOM_COP=distance between the COM and COP position in the frontal plane at seat-off, APCOP and APCOM=peak-to-peak COP and COM displacement in the sagittal plane, respectively, APCOP_mid and APCOM_mid=distance between the COP and COM position relative to the midpoint between the malleoli in the sagittal plane at seat-off, respectively; positive and negative values reflect a position anterior and posterior to the midpoint, respectively, APCOM_COP=distance between the COM and COP position in the sagittal plane at seat-off, APCOPa and APCOPu=distance between the affected limb COP and unaffected limb COP relative to the respective medial malleolus in the sagittal plane at seat-off, SB1, SB2, SB3, SB4=2.54, 5.08, 7.62 and 10.16cm solid blocks, respectively. CB1 and CB2=2.72 and 6.63kg compliant blocks, respectively. Quart and half=quart-foot and half-foot asymmetrical conditions.
6.5.2 Temporal measures

There was no main effect of condition for the Ttotal ($F_{(3.77,45.25)} = 1.55, p > 0.05$) or for Tp1 and Tp2 (data not shown). With the half-foot condition there was a trend towards increased time to complete the task, however the difference was not significant (Table 6.2).

6.5.3 Weight-bearing measures

There was a main effect of condition for affected limb weight-bearing at seat-off ($F_{(8,96)} = 16.77, p < 0.001$) (Table 6.2). Affected limb weight-bearing was significantly larger for all conditions compared with baseline. Pairwise comparison revealed that affected limb weight-bearing with the SB1 condition was significantly lower compared with all other conditions except the quart-foot position and affected limb weight-bearing with the SB4 condition was significantly larger than with the SB1, SB2 and SB3 conditions. Pairwise comparison also revealed a significantly higher affected limb weight-bearing with the half-foot position compared to all other conditions, with the half-foot condition demonstrating the greatest amount of affected limb weight-bearing at seat-off. Individual results demonstrated that the increase in affected limb weight-bearing was not consistent for all participants with the solid and compliant block conditions or with the quart-foot condition (Figure 6.1, 6.2, and 6.3). However, all participants increased affected limb weight-bearing with the half-foot asymmetrical condition (Figure 6.3).
Figure 6.1: Affected limb weight-bearing for each participant with the baseline and solid block conditions

SB1=2.54cm block, SB2=5.08cm block, SB3=7.62cm block, SB4=10.16cm block, VGRF=vertical ground reaction force.
Figure 6.2: Affected limb weight-bearing for each participant with the baseline and compliant block conditions

CB1=2.72kg compliant block, CB2=6.63kg compliant block, VGRF=vertical ground reaction force.
Figure 6.3: Affected limb weight-bearing for each participant with the baseline and asymmetrical foot conditions

quart=quart-foot position, half=half-foot position, VGRF=vertical ground reaction force.
6.5.4 Displacement measures

6.5.4.1 Frontal plane

There was no main effect of condition for MLCOP ($F_{(1.84,22.07)}=1.77, p>0.05$) or MLCOM ($F_{(2.82,30.96)}=1.45, p>0.05$). There was a trend toward increased MLCOM displacement across all conditions, however the values did not differ significantly from baseline (Table 6.2). There was a main effect of condition for MLCOP_midline ($F_{(8,88)}=19.70, p<0.001$). The MLCOP_midline was significantly different for all conditions compared with baseline. The mean COP position was located toward the unaffected limb relative to midline with the baseline, SB1, SB2, SB3, SB4, CB1 and CB2 conditions and toward the affected limb relative to midline for the quart-foot and half-foot conditions (Table 6.2). Pairwise comparison revealed no difference in COP position between the SB1, SB2, SB3, SB4, CB1 and CB2 conditions and no difference between the quart-foot, SB4, CB1 and CB2 conditions. The observed shift with the half-foot condition was greater than with all other conditions.

Individual results demonstrated movement of the COP position toward the affected limb for ten of thirteen participants in the SB1 condition and eleven of thirteen participants with the remaining solid block conditions (Figure E1 in Appendix E). The COP position moved toward the affected limb relative to midline for twelve of thirteen participants with the two compliant block and quart-foot conditions (Figure E2 and E3 in Appendix E). With the half-foot asymmetrical foot condition, the COP was positioned more toward the affected limb relative to midline in all participants (Figure 6.4).
Figure 6.4: Distance between the COP position and midpoint between the malleoli in the frontal plane (MLCOP_midline) at seat-off for each participant with the baseline and half-foot conditions.

half=unaffected limb placed a half-foot length ahead of the affected limb
There was a main effect of condition for the MLCOM_midline ($F_{(8,88)}=11.52$, $p<.001$). The MLCOM_midline was different for all conditions, except SB2 compared with baseline. The COM moved toward midline with the SB1, SB3, SB4, CB1 and CB2 conditions. With the quart-foot and half-foot conditions, the COM position was located toward the affected limb relative to the midline (Table 6.2). There was no difference in the shift of the COM toward midline between the SB1, SB3, SB4, CB1, CB2 and quart-foot conditions. The observed shift with the half-foot condition was greater than with all other conditions.

Individual results demonstrated inconsistent change in the COM position relative to midline with the solid block, compliant block and quart-foot conditions (Figure E4, E5 and E6 in Appendix E). The COM position relative to midline moved toward the affected limb for all participants with the half-foot asymmetrical condition (Figure 6.5).
Figure 6.5: Distance between the COM position and midpoint between the malleoli in the frontal plane at seat-off (MLCOM_mid) for each participant with the baseline and half-foot conditions

half=unaffected limb placed a half-foot length ahead of the affected limb
There was no main effect of condition for the MLCOM_COP ($F_{(8,88)}=.91, p>0.05$). There was a trend toward increased MLCOM_COP at seat-off across all conditions compared with baseline, however the values did not differ significantly from baseline (Table 6.2).

6.5.4.2 Sagittal plane

There was no main effect of condition for the APCOP ($F_{(1.66,19.91)}=2.05, p>0.05$). A trend toward increased APCOP was observed across all conditions compared with baseline, however the values did not reach significance (Table 6.2).

There was a main effect of condition for the APCOM ($F_{(3.38,37.19)}=32.95, p<0.001$). The APCOM was larger for the CB1, CB2, quart-foot and half-foot conditions compared with baseline. Pairwise comparison revealed a significantly greater APCOM with the half-foot condition compared with all other conditions (Table 6.2). Individual results demonstrated that the peak-to-peak COM displacement in the sagittal plane was larger for ten of twelve participants with the compliant block conditions. With the two asymmetrical foot conditions, the APCOM distance was larger for all participants.

There was a main effect of condition for the APCOP_midpoint ($F_{(3.18,34.95)}=11.24, p<0.001$). The APCOP_midpoint was different with the CB1, CB2, quart-foot and half-foot conditions compared with baseline. With the two compliant block conditions, the COP position was further forward compared with baseline (Table 6.2) and with the two asymmetrical foot conditions the COP position was further posterior compared with baseline (Table 6.2). Pairwise comparison revealed greater posterior movement of the COP with the half-foot condition compared with the quart-foot condition. Individual results demonstrated that movement of the COP position relative to the midpoint between the malleoli at seat-off in the sagittal plane was not consistent for all participants with the compliant block and asymmetrical foot conditions.

There was a main effect of condition for the APCOM_midpoint ($F_{(8,88)}=33.44, p<0.001$). The APCOM_midpoint was different with the CB1, CB2, quart-foot and half-foot conditions.
compared with baseline. The COM position at seat-off was more anterior with the CB1 and CB2 conditions compared with baseline (Table 6.2) and with the two asymmetrical foot conditions, the COM position was more posterior compared with baseline (Table 6.2). Pairwise comparison revealed greater posterior movement of the COM with the half-foot condition compared with the quart-foot condition. Individual results demonstrated inconsistent change of COM position at seat-off in the sagittal plane with the compliant block condition. In contrast, a consistent change in APCOM_midpoint was observed with the asymmetrical foot conditions (Figure E7 and E8 in Appendix E).

There was a main effect of condition for the APCOM_COP ($F_{(8,88)}=5.77, p<0.001$). The distance between the COM and COP position at seat-off in the sagittal plane was larger with the two asymmetrical foot conditions compared with baseline (Table 6.2). Individual results demonstrated a consistent change in APCOM_COP with the half-foot asymmetrical condition, compared with the quart-foot asymmetrical condition (Figure E9 and E10 in Appendix E).

There was no main effect of condition for the APCOPa at seat-off ($F_{(1.40,15.37)}=1.50, p>0.05$). There was a trend towards a smaller distance between the affected limb COP position relative to the malleolus at seat-off, however the values did not reach significance (Table 6.2).

There was a main effect of condition for the APCOPu at seat-off ($F_{(2.70,29.67)}=12.13, p<0.001$). The APCOPu was different with the SB4, CB1, CB2, quart-foot and half-foot condition compared with baseline. With the SB4, CB1 and CB2 condition, the COP was positioned further forward compared to baseline (Table 6.2). Pairwise comparison revealed the largest forward movement of the COP with the CB1 condition compared with the SB4 and CB2 condition. With the two asymmetrical foot conditions, the COP was positioned more posterior compared with baseline (Table 6.2). Individual results demonstrated that the change in position of the COP of the unaffected limb relative to baseline was not consistent across all participants with the compliant block and asymmetrical foot conditions.
6.6 Discussion

The purpose of this study was to investigate the effect of CIM strategies for the lower limb on temporal, weight-bearing and displacement measures of STS performance in people with stroke. Three strategies were investigated including placement of the unaffected limb on a solid block or a compliant (foam) block and an asymmetrical foot position with the unaffected limb placed ahead of the affected limb. Four solid block heights, two compliant block densities and two asymmetrical foot positions were investigated. The group of people with stroke who participated in this study were able to walk into the MPL for testing, ascend/descend stairs and STS without using their arms, suggesting a high level of function among this group of participants. Consequently, findings from this study are limited to people with stroke demonstrating a high level of physical function and are able to perform the STS task without using their arms.

Two participants in this study were unable to perform the STS task with all solid block heights, both compliant blocks and both asymmetrical foot positions. Both participants were likely unable to perform the STS task with all of the strategies due to a lower level of function compared with the remaining participants and inability to bear sufficient weight or balance on the affected limb when the unaffected limb was placed on the solid block, compliant block or ahead of the affected limb and rise to stand without using their arms. In addition, they were likely unable to generate sufficient muscle force and appropriate joint moments bilaterally, or unilaterally at the hip and knee to perform the STS task with their unaffected limb placed in a position with altered knee and hip angles and complete the STS task.

6.6.1 Solid block strategies

Time to complete the STS task was not significantly affected by the solid block conditions. A longer time to complete the task may suggest greater difficulty performing the task compared with baseline. This finding suggests that the solid block conditions did not increase task difficulty as reflected by time.
Weight-bearing of the affected limb at seat-off was greater with all solid block conditions (48.38–51.59%) compared with baseline (45.78%). Affected limb weight-bearing with the highest block (SB4) was greater than with the SB1, SB2 and SB3 conditions indicating that the higher block resulted in the largest constrained use of the unaffected limb during STS. The findings as reported in figure 6.2 also suggest greater affected limb weight-bearing as block height increased.

Greater weight-bearing through the affected limb as demonstrated by a greater VGRF would suggest greater generation of muscle force and joint moments of the affected limb at seat-off, compared with baseline using the solid block strategies. Based on findings reported by Roy et al. (6) and Roy et al. (7), greater affected limb weight-bearing with an asymmetrical foot position strategy resulted in a greater knee extensor moment of the affected limb at seat-off, changes to the hip extensor moment did not reach significance. Consequently, participants in this study likely generated a greater knee joint extensor moment of the affected limb at seat-off with the solid block strategies.

Findings with this CIM strategy are consistent with those reported by Rocha et al. (8) who investigated the effect of using a solid block strategy in a group of thirteen participants with chronic stroke (greater than six months); the average age and time since onset was reported as 60 years and 43.7 months, respectively. Less weight-bearing asymmetry, measured as the index of asymmetry (IA), was found when the unaffected limb was placed on a solid block equal to 25% of chair height during STS compared with the feet placed in parallel on two force platforms. An IA of 0% reflected equal weight-bearing on both limbs while a positive or negative value reflected greater weight-bearing on the unaffected or affected limb, respectively. The mean IA value at baseline and with the solid block was 23% and 10%, respectively (values obtained visually from a graph of the results) (8). Although weight-bearing asymmetry was reduced, equal loading of the two limbs was not achieved (8). The height of the block used in the study by Rocha et al. (8) is most comparable to the highest block (SB4) used in the present study.
In the current study, affected limb weight-bearing at baseline and with the SB4 condition was 45.78% and 51.59%, respectively, with a value of 50% reflecting equal weight-bearing on both limbs. The difference in the amount of change reported by the two studies may be due to a difference in baseline values and consequently the amount of change required to achieve weight-bearing symmetry. Greater affected limb weight-bearing was anticipated with the solid block conditions based on findings reported by Rocha et al. (8) and may be due to placement of the unaffected limb in a position of biomechanical disadvantage, achieved through larger hip and knee flexion angles and changes in muscle length, which increase the difficulty of using the unaffected limb during STS.

Sit-to-stand performance with the solid block conditions did not affect total displacement of the COP (MLCOP) or COM (MLCOM) or the distance between the COP and COM (MLCOM_COP) in the frontal plane at seat-off. These findings suggest that STS with the solid block conditions did not challenge balance or destabilize movement in the frontal plane in participants who were able to perform the task with all block heights. We anticipated larger total COP and COM displacement due to greater loading of the affected limb, increased task difficulty and a greater need to stabilize frontal plane movement, however this was not observed. Two possible reasons for not observing changes to these measures was the high level of physical functioning of the group of participants with stroke and that STS performance with the solid block strategies did not increase task difficulty, as reflected by time.

The distance between the COM and COP in the frontal plane was included as a measure because it has been reported as a better measure of balance than COM or COP displacement alone (15). That this measure was not affected by the solid block strategies suggests that this CIM strategy would be safe to use in a rehabilitation program with minimal supervision because it does not have a destabilizing effect on STS performance.

Three of the block conditions (SB1, SB3 and SB4) resulted in a shift of the COP and COM towards the affected limb, with the COP and COM coming very close to midline with the SB4
condition (.02±1.48 and .01±1.09 respectively). Movement of the COP and COM toward midline was anticipated due to greater affected-limb weight-bearing and is a desired outcome as it reflects a more centralized position of the COP and COM. A COP and COM position closer to midline at seat-off would suggest fewer postural corrections are needed to maintain the frontal plane position of the COP and COM within the BoS. This finding may explain why there was no increase in the peak-to-peak frontal plane COP and COM displacement.

The solid block conditions did not affect total displacement of the COP (APCOP) or COM (APCOM) in the sagittal plane or the distance between the COM and COP (APCOM_COP) at seat-off in the sagittal plane indicating that the solid block conditions were not destabilizing to sagittal plane balance. These three measures were found to be the same in people with stroke as in healthy adults by the author (Chapter 5) and were not anticipated to change with this CIM strategy. They were included in the present study to establish any effect of destabilization to sagittal plane balance.

The COP position under the affected limb at seat-off in the sagittal plane (APCOPa) did not change with the solid block conditions. The COP position under the unaffected limb at seat-off in the sagittal plane (APCOPu) was more anterior with the SB4 condition compared to baseline. Movement of the COP position under the unaffected limb with the SB4 condition was not expected and the implications of this finding remain unclear.

6.6.2 Compliant (foam) block strategies

Time to complete the STS task was not affected by the compliant block conditions. The height of the compliant blocks was the same as the SB4 condition, however they had an added effect of altering sensory input from the unaffected limb. This finding suggests that sensory manipulation of the unaffected limb did not increase difficulty of performing the STS task as reflected by time in this group of participants with stroke.
Affected limb weight-bearing at seat-off was greater with the compliant block conditions (50.72 and 51.00% for CB1 and CB2, respectively) compared with baseline (45.78%). As described with the solid block strategies, greater affected limb weight-bearing suggests greater muscle force generation and extensor joint moments at the knee at seat-off during STS.

Findings from this study are not consistent with those reported by Brunt et al. (1) who investigated the effect of placing the unaffected limb on a dense foam block in a group of ten people with chronic stroke. The mean age and time since stroke onset were 65.9 years and 43.2 months, respectively. Brunt et al. (1) compared the peak vertical ground reaction force (VGRF), expressed as a percent of body weight, of the affected and unaffected limb and reported a significant difference between the affected (53%) and unaffected limb (69%) at baseline. Although the peak VGRF of the affected limb was higher (56%) with the compliant block, it remained significantly lower than the peak VGRF of the unaffected limb (66%). Values were greater than 50% because they reflect the peak VGRF, which is greater than 100% of body weight during STS performance (2).

In the present study we investigated the change in affected limb weight-bearing as a percent of the total weight-bearing at seat-off and reported a mean change from baseline of 5.08% with the compliant block conditions; a value larger than that reported by Brunt et al. (1). The different results reported in the two studies may be due to a smaller number of participants included in the study by Brunt et al. (1) or due to a difference in methodology for investigating changes to affected limb weight-bearing.

The larger affected limb weight-bearing with this CIM strategy may be due to a biomechanical disadvantage of the unaffected limb, as discussed with the solid blocks, combined with sensory manipulation of the unaffected limb. Sensory manipulation of the unaffected limb may reduce confidence in placing weight through the unaffected limb, thereby resulting in a higher amount of weight through the affected limb. The height of the compliant blocks was the same as the SB4 condition, which also resulted in greater weight-bearing of the affected limb. Therefore, it cannot
be determined if greater weight-bearing of the affected limb with the compliant blocks is due to placement of the unaffected limb in a position of biomechanical disadvantage, sensory manipulation or a combination of both.

Examination of the balance measures revealed no change to the peak-to-peak COP and COM displacement and no change to the distance between the COM and COP at seat-off in the frontal plane. The compliant block conditions affect sensory input from the unaffected limb and could destabilize STS performance. Therefore, we anticipated an increase in these measures and a challenge to balance in the frontal plane. The lack of a significant change in these measures suggests that STS with the compliant blocks was not destabilizing for participants who were able to rise to stand with this CIM strategy.

The COP and COM position in the frontal plane at seat-off was shifted toward midline with the compliant block conditions compared to baseline. Similar to the solid block conditions, movement of the COP and COM toward midline was anticipated to coincide with greater affected-limb weight-bearing. This is a desired outcome as it reflects a more centralized position of the COP and COM as seen in healthy older adults.

The compliant block conditions did not change the total COP displacement in the sagittal plane or the distance between the COM and COP at seat-off in the sagittal plane compared with baseline. However, the total COM displacement in the sagittal plane was greater with the compliant blocks compared with baseline. The larger COM displacement suggests a challenge to balance in this plane using this strategy, possibly as a consequence of impaired sensory input from the unaffected limb.

Both the COP and COM position at seat-off in the sagittal plane, APCOP_midpoint and APCOM_midpoint, respectively were further forward with the compliant block conditions compared with baseline. These findings were not observed with the solid block conditions, therefore they are likely due to sensory manipulation of the unaffected limb which had a destabilizing effect on sagittal plane STS performance. The COP and COM position at seat-off
with the compliant block conditions may reflect a strategy for minimizing the number of postural corrections needed to stabilize the COM over the second BoS.

There was no change to the COP position under the affected limb at seat-off in the sagittal plane (APCOPa) with the compliant block conditions compared with baseline. In contrast, the COP position under the unaffected limb at seat-off was further forward compared with baseline. Movement of the COP position under the unaffected limb with the compliant block conditions was not expected and the implications of this finding remain unclear.

### 6.6.3 Asymmetrical foot position strategies

There was a trend toward increased time to complete the STS task with the asymmetrical foot conditions, however the values were not significantly different from baseline. Placement of the unaffected limb ahead of the affected limb increased the AP dimension of the BoS. This finding suggests that the change in BoS did not increase task difficulty as reflected by time.

Weight-bearing of the affected limb at seat-off was greater with the asymmetrical foot conditions (49.92 and 55.13% for the quart and half-foot conditions, respectively) compared with baseline (45.78%). Affected limb weight-bearing with the half-foot condition was greater compared with the quart-foot condition indicating that the half-foot condition resulted in a larger constrained use of the unaffected limb during STS and biased weight-bearing toward the affected limb. As described with the solid and compliant block strategies, greater affected limb weight-bearing suggests larger muscle force generation and knee extensor moments of the affected limb at seat-off during STS.

Findings from this study are consistent with results reported by Rocha et al. (8), Brunt et al. (1), Roy et al. (6) and Lecours et al. (3). All four authors reported improved weight-bearing symmetry in people with stroke when performing the STS task with the unaffected limb placed ahead of the affected limb compared with the feet placed in parallel. The number of participants in these studies ranged from 10-17 with a mean age ranging between 49.7-65.9 years and a mean
time since stroke onset ranging from 38.4-43.7 months. Each study compared one asymmetrical foot position, unaffected limb placed ahead of the affected limb, to the feet placed in parallel. Roy et al. (6) and Lecours et al. (3) placed the unaffected limb half a foot length ahead of the affected limb and the remaining two studies described the altered foot position using joint angles. Rocha et al. (8) and Roy et al. (6) investigated changes to the index of asymmetry (IA), Brunt et al. (1) compared peak VGRF, expressed as a percent of body weight, of the affected limb with the unaffected limb and Lecours et al. (3) examined changes to the ratio of weight-bearing, with values less than one indicating greater weight-bearing of the unaffected limb and values larger than one indicating greater weight-bearing of the affected limb. Rocha et al. (8) reported a significantly smaller IA with the asymmetric foot condition (19%) compared with baseline (23%), (values obtained visually from a graph of the results). Roy et al. (6) reported a similar change from 20% to 11.1%. Brunt et al. (1) reported no difference in weight-bearing between the two limbs with the asymmetrical foot condition compared with baseline, suggesting symmetry of weight-bearing between the two limbs. Lecours et al. (3) reported a significantly greater weight-bearing ratio with the asymmetrical foot condition (.87) compared with baseline (.67) demonstrating greater loading of the affected limb.

In the present study, the quart-foot condition resulted in symmetry of weight-bearing between the two limbs while the half-foot condition resulted in greater loading of the affected limb than the unaffected limb. Despite a similar mean age and time since stroke onset between studies, the findings from the present study suggest that the participants may have been more willing to accept weight on the affected limb thereby leading to greater loading of the affected limb with the asymmetrical foot conditions compared with the studies discussed above.

One study was found that reported no significant change to affected limb weight-bearing with the asymmetrical foot condition (10). Camaragos et al. (10) compared STS performance with the unaffected limb placed ahead of the affected limb in a group of 12 people with chronic stroke; mean age and time since stroke onset was 68 years and 92 months, respectively. Weight-bearing
asymmetry was measured as a ratio, as described above, and the value with the asymmetrical foot condition (.74) was not significantly different from baseline (.64). The author did not describe the methodology used for foot placement. Therefore, a non-significant change with the asymmetrical foot condition may be due to differences in methodology of foot placement or the larger mean time since stroke onset in this group of participants.

The asymmetrical foot conditions did not affect the total displacement of the COP (MLCOP) or COM (MLCOM) or the distance between the COM and COP in the frontal plane at seat-off (MLCOM_COP) compared with baseline. These findings suggest that the asymmetrical foot positions did not significantly challenge frontal plane balance or destabilize frontal plane movement in this group of people with stroke.

There was a shift in the COP and COM position relative to the midline in the frontal plane at seat-off with the asymmetrical foot conditions compared with baseline. The COP and COM position was shifted toward the affected limb relative to midline. The shift in the COP and COM with the quart-foot condition was not different compared with the SB4, CB1 and CB2 conditions suggesting that STS with the quart-foot condition centralizes the COP and COM position despite being located toward the affected limb relative to midline. In contrast, the shift in the COP and COM with the half-foot condition was greater compared with all other conditions, reinforcing constraint of the unaffected limb and greater use of the affected limb during STS with this CIM strategy.

The findings from the present study are consistent with results reported by Duclos et al. (9). Duclos et al. (9) investigated STS performance with the unaffected limb placed half a foot length ahead of the affected limb in a group of eighteen people with chronic stroke. The mean age of participants was 50 years and time since stroke onset ranged from 6 months to 8 years. Three participants were unable to rise to stand with the asymmetrical foot condition. A picture of the results demonstrated a COP path toward the unaffected limb relative to midline at baseline and
with the asymmetrical foot condition. Mean values for COP position at seat-off, obtained from the picture were 3cm with baseline and 1cm with the asymmetrical foot condition.

In the present study, the mean position of the COP was 1cm from midline at seat-off at baseline. Values of -0.22cm and -1.75cm were reported for the quart-foot and half-foot conditions, respectively. The difference in values reported between studies may be due to increased willingness to accept greater loading of the affected limb in the group of participants in the present study.

The asymmetrical foot conditions did not affect the total displacement of the COP (APCOP) in the sagittal plane compared with baseline, suggesting that this CIM strategy did not challenge sagittal plane balance as reflected by total AP displacement of the COP. In contrast, there was a larger total COM (APCOM) displacement in the sagittal plane and a larger distance between the COM and COP position at seat-off with the asymmetrical foot conditions compared to baseline. These finding are likely the result of an increase in the AP dimension of the BoS with the asymmetrical foot conditions and reflect more anterior movement of the COM at the end of the task compared with the feet placed in parallel and greater COM displacement with respect to the COP. Consequently, these findings likely do not reflect a challenge to sagittal plane balance.

Both the COP and COM position in the sagittal plane at seat-off were more posterior with the asymmetrical foot conditions compared with the position at baseline. The asymmetrical foot conditions increased the AP dimensions of the BoS such that the midpoint between the malleoli in the sagittal plane moves forward. Posterior movement of the COP and COM position at seat-off with the asymmetrical foot conditions is likely the result of anterior movement of the midpoint between the malleoli and greater weight on the more posteriorly placed affected limb.

There was no change in the COP position of the affected limb (APCOPa) with the asymmetrical foot conditions compared with baseline. In contrast, the COP position of the unaffected limb moved posteriorly with the asymmetrical foot conditions compared with baseline. This finding
was anticipated due to a forward position of the unaffected limb and the smaller weight-bearing on this limb.

**6.6.4 Clinical Relevance**

People with stroke have demonstrated lower weight-bearing of the affected limb compared with the non-dominant limb of healthy adults, greater peak-to-peak COP and COM displacement in the frontal plane and a shift of the COP and COM toward the unaffected limb in the frontal plane at seat-off when performing the STS task (Chapter 5). These findings suggest balance impairment and asymmetry of movement. Therapeutic goals in rehabilitation may include greater weight-bearing of the affected limb and centralization of the COP and COM during movement. The effect of three CIM strategies was investigated in this study as potential treatment options for achieving these goals.

In a single test session all strategies resulted in greater affected limb weight-bearing and a shift of the COP and COM toward the midline in the frontal plane. Benefits of greater loading on the affected limb may include increases in muscle strength through greater muscle activation or increased confidence placing weight through the affected limb by maximizing joint compression and augmenting sensory awareness of the limb. The CIM strategies investigated in this study may provide a functional method for training muscle strength and joint position sense of the affected limb.

Another possible reason for lower affected limb weight-bearing in people with stroke may be due to a learned non-use of the affected limb that may develop early (less than six months) after a stroke when attempts to perform the STS task using the affected limb with equal weight-bearing are unsuccessful (16). With repeated unsuccessful attempts, a compensatory pattern for performing the STS task with greater weight-bearing on the unaffected limb may be reinforced (16). Greater use of the affected limb was observed in this study suggesting that learned non-use accounts for a component of the asymmetry and that training with one of the CIM strategies may
reverse learned non-use through repeated successful practice of the STS task with increased use of the affected limb (16).

Practice with any one of these strategies may lead to improved symmetry of movement and less deviation of the COP and COM toward the unaffected limb at seat-off. Given the potential benefits of STS practice with the CIM strategies, further investigation is warranted to determine the effects of training STS with the CIM strategies and to determine who may receive the most benefit from training with each type of strategy.

6.7 Conclusions

The effects of three CIM strategies were investigated in this study including placement of the unaffected foot on a solid block or a compliant (foam) block and placement of the unaffected limb ahead of the affected limb. Findings from this study demonstrated greater weight-bearing of the affected limb using all of the CIM strategies, with the largest change observed with the half-foot condition.

None of the strategies investigated in this study altered balance in the frontal plane as indicated by the total excursion of the COP or COM (MLCOP and MLCOM). However, all strategies resulted in a significant shift in the COP and COM position toward midline at seat-off. Only the compliant block and asymmetrical foot conditions altered measures of AP displacement including increased COM displacement and position of the COP and COM at seat-off.

There was no change to COP position under the affected limb with any of the strategies, however there were changes to the COP position under the unaffected limb with the highest solid block condition, both compliant block conditions and both asymmetrical foot conditions.

Pairwise comparison revealed no difference in findings between the two compliant block conditions suggesting that altered sensory input to the unaffected limb is responsible for changes in STS performance and not the specific density of the foam block. Consistency of participant
response was greatest with the half-foot condition for all measures demonstrating significant change providing confidence in the effect of this CIM strategy.

Given the observed changes to affected limb weight-bearing, frontal plane and sagittal plane balance with the compliant block and asymmetrical foot conditions it is recommended that both CIM strategies be included in a randomized controlled intervention trial to determine immediate changes to STS performance and retention of any changes six months following the end of training.

6.8 References


Chapter 7

General Discussion and Future Research

Stroke is the leading cause of adult neurological disability in Canada (1) and it is estimated that 40,000 people will have a stroke every year in Canada (2). People with stroke have a higher risk of falling than their age matched peers with most falls occurring during transition movements including STS (3). When rising to stand from sitting, people with stroke have demonstrated greater weight-bearing on the unaffected limb and a larger COP displacement in the frontal plane (4-6). These two characteristics of STS in people with stroke may contribute to the higher risk of falling during transition movements (4). Consequently, increased weight-bearing of the limb affected by the stroke and decreased COP displacement in the frontal plane are often two treatment goals in people with stroke. Constraint-induced movement (CIM) therapy is a strategy used to achieve these two goals during STS in people with stroke (7-9).

The intent of this research was to investigate sit-to-stand (STS) performance in people with stroke and contribute to the evidence base for rehabilitation practice. The primary objective of this thesis was to investigate the effect of CIM strategies on STS performance in people with stroke; specific measures included time to complete the task, affected limb weight-bearing and measures of balance in the frontal and sagittal plane. Secondary objectives of this thesis included investigation of methods describing STS performance in people with stroke, establishing within and between day reliability of measures of STS performance and to contribute to the knowledge base regarding impairments in STS performance in people with stroke compared to healthy adults using traditional and novel measures. Four studies were conducted to achieve these objectives.
7.1 Overview of Findings

The first study (Chapter 3) investigated the methodology for describing STS performance in people with stroke. This study was essential to establish a method of describing STS performance in people with stroke to carry forward in subsequent studies. The STS task requires movement from a stable three-point base of support (BoS) to a less stable two-point BoS (10).

Two common methods of describing the STS task include dividing the task into phases (11) and identification of discrete events during the STS cycle (12). Both Schenkman et al. (11) and Etnyre et al. (12) described STS performance in healthy adults and it was demonstrated that these methods are not as appropriate for describing the task in people with stroke. For example, Schenkman et al. (11) marked the transition between two phases as the point of maximum ankle dorsiflexion. Descriptive findings reported in Chapter 3 demonstrated that maximum ankle dorsiflexion of the affected and unaffected limb do not occur at the same time creating the potential for inconsistency with identification of this point in the STS cycle. Etnyre et al. (12) reported a peak vertical ground reaction force (VGRF) under the two feet following seat-off that occurred at the end of the rise in force. The findings from study one (Chapter 3) demonstrated that the peak VGRF is not easily identified in people with stroke and does not always occur at the end of the rise in VGRF. Therefore, comparison of peak VGRF in people with stroke and healthy adults is inappropriate because it does not always occur at the same point in the STS cycle. Furthermore, it is inappropriate to compare this measure within a group of people with stroke due to variability in timing of the total and single limb peak VGRFs.

Seat-off, when the buttocks leave the chair, is a critical point in the STS cycle because the participant’s body weight is fully distributed over the two lower limbs after this point in the cycle. Schenkman et al. (11) identified seat-off as the point where the VGRF under the feet began to increase in a weight-bearing direction, while Etnyre et al. (12) identified seat-off with a voltage gated switch placed under the participant’s right buttock. Findings from study one (Chapter 3) demonstrated that an increase in the VGRF under the feet corresponds with maximum loading of
the VGRF under the chair and therefore this point in the STS cycle does not reflect transition to the second BoS. A voltage gated switch placed under one of the participant’s buttocks may not be appropriate in people with stroke who may asymmetrically unweight their buttocks during performance of the STS task.

Based on the findings from study one (Chapter 3) the author recommended describing the STS task in two phases in people with stroke using seat-off, as the marker between the two phases, with seat-off defined by the VGRF under the chair reaching zero. In addition, it was recommended that STS performance be described at the point of seat-off, because this reflects the transition between the first and second BoS and represents the same point in the STS cycle in all participants. Establishing a consistent method of describing STS performance in people with stroke and healthy adults would make it easier to compare findings from different studies and compare STS performance with other clinical populations.

The second study (Chapter 4) investigated the reliability of temporal, weight-bearing and displacement measures of STS performance in people with stroke and healthy adults. Reliability of measures must be demonstrated to provide confidence in the results of a study that may be used to inform clinical decisions. Common measures of STS performance in people with stroke include time to complete the task, affected limb weight-bearing and balance in the frontal and sagittal planes. Eng et al. (13) demonstrated reliability of affected limb weight-bearing during STS in people with stroke, however no other studies were found which investigated reliability of measures of STS performance in this clinical population. Findings from the second study demonstrated moderate (>0.50) to high (>0.70) ICC values for within and between day reliability of commonly used measures of STS performance in people with stroke including time to complete the task, weight-bearing of the affected and unaffected limb as well as measures of frontal and sagittal plane displacement. Establishing reliability of measures of STS performance provides confidence in findings reported in studies and treatment decisions based on the findings.
Measures of weight-bearing demonstrated very high within and between day reliability (ICC’s >0.9). The remaining measures demonstrated higher within day than between day reliability.

Results from previous studies have demonstrated weight-bearing asymmetry, (more weight through the unaffected limb compared with the affected limb), and impaired balance (increased frontal plane displacement of the COP) in people with stroke performing the STS task (4-6). Based on the findings from study one the author recommended examination of STS performance at seat-off, identified by a VGRF of zero under the chair, because this clearly indicates the transition between the first and second base of support. Based on this recommendation, the third study (Chapter 5) of this thesis investigated STS performance in people with stroke and healthy age and sex matched adults using measures described in the literature and novel measures examining STS performance at seat-off.

Findings from study three confirmed results from previous studies including greater time needed to complete the task in people with stroke compared with healthy adults, weight-bearing asymmetry and greater frontal plane COP displacement in people with stroke (4-6). Findings from this study provided further evidence of differences in STS performance between people with stroke and healthy adults by demonstrating a shift in COP and COM toward the unaffected limb relative to the midline in the frontal plane at seat-off. In addition, people with stroke placed their COM further forward at seat-off compared with healthy adults, which may reflect a strategy for reducing muscular strength required to perform the task or a strategy for minimizing the number of postural corrections required to stabilize the COM in the second BoS. Lastly, the findings demonstrated a more anterior position of COP under the affected limb in people with stroke at seat-off.

Advanced understanding of STS performance in people with stroke highlight potential areas for rehabilitation to improve STS performance in people with stroke and provides specific measures for assessing change following treatment intervention. Furthermore, knowledge of STS
performance provides greater insight into strategies used by people with stroke for performing the STS task.

The purpose of the fourth study (Chapter 6) was to investigate the effect of constraint-induced movement (CIM) strategies on STS performance in people with stroke in a single test session. The three CIM strategies investigated were placement of the unaffected limb on a solid block and a compliant (foam) block and an asymmetrical foot position, with the unaffected foot placed ahead of the affected foot. Four solid block heights, two foam densities and two asymmetrical foot positions were investigated.

Compared to baseline, there was greater affected limb weight-bearing and a shift of the COP and COM toward midline in the frontal plane with all of the CIM strategies. Only the compliant block and asymmetrical foot position strategies altered COP and COM position in the sagittal plane suggesting a challenge to balance in this plane. Consistency of response across subjects on all measures was highest with the asymmetrical foot position strategies. The findings from study four advances knowledge of the effect of CIM strategies on STS performance in people with stroke and suggests strategies that could be used in a clinical trial designed to improve STS performance in this clinical population.

7.2 Limitations

Findings from this research provide a greater understanding of STS performance in people with stroke and the effect of CIM strategies on STS performance in a single session. Several limitations of the work completed are discussed.

Firstly, we had a small sample size. Although we demonstrated a significant difference between people with stroke and healthy adults and differences in people with stroke using the CIM strategies (Chapter 5 and 6), several measures demonstrated a trend toward change but did not reach significance. A larger sample size may have resulted in identification of a greater number of differences between stroke and the healthy adults or in people with stroke using the CIM
strategies. Furthermore, a larger sample size may have permitted sub analysis of the data based on baseline weight-bearing values to determine if the effect of the CIM strategies is dependent on baseline values.

In addition, participants were likely functioning at a relatively high level in order to meet the inclusion criteria, including ability to rise to stand from sitting without the use of arms. Therefore, our findings may not be generalizable to a larger population of people with stroke, for example, those who need the use of arms to rise to stand from sitting.

Although participants were likely functioning at a high level we noted inconsistency in response to the CIM strategies among participants. The inconsistency of response suggests heterogeneity among participants, which may be demonstrated by the range of affected limb weight-bearing with baseline STS performance (36.15-52.12%). A larger sample size may have permitted analysis of subpopulations based on functional status or baseline weight-bearing performance, thereby allowing generalization of the results to people with stroke with similar baseline values.

Both global and discrete measures of STS performance were investigated in this study. Total COP and COM displacement in the frontal and sagittal plane are examples of global measures and are described in previous studies. The position of the COP and COM as well as the distance between the COP and COM at seat-off in the frontal and sagittal plane are examples of discrete measures of STS performance in people with stroke. This seat-off point in the STS cycle was chosen because it represents the same point in the STS cycle in all participants (Chapter 3) and because the measures at this point in the STS cycle demonstrated within and between day reliability (Chapter 4 and Appendix D). However, the discrete measure provides a ‘snapshot’ of performance and does not describe performance from the beginning to the end of the STS cycle. Additional measures may provide additional insight of STS performance in people with stroke. For example, one may suggest investigating the average WB, and COP or COM position for 10% (5% pre and post seat-off) of the STS cycle, or the average of these measures over the STS cycle pre and post seat-off. One additional suggestion may be to divide the task into 5% increments.
and examine the average value for each measure within each increment providing detail of the measures over the entire STS cycle.

Lastly, findings from this thesis provided a greater understanding of the effect of CIM strategies on STS performance in people with stroke. The effect of the CIM strategies was investigated in a single session and the findings demonstrated greater loading of the affected limb and a centralized position of the COP and COM. Based on these findings one may suggest that training with a CIM strategy may lead to improved symmetry of performance in people with stroke, however the effect of using a CIM strategy in a training study was not investigated. Consequently, the results from this thesis are limited with respect to determining the potential effect of CIM strategies over time based on the findings from a single test session.

7.3 Recommendations

Several methodological and clinical recommendations emerged from the studies contained in this thesis and include the following:

1. When describing STS performance in people with stroke, it is recommended that the task be described in two phases using seat-off, defined by a VGRF of zero under the chair, as the marker between the two phases.

2. A larger frontal plane COP displacement in people with stroke compared with healthy adults suggests balance impairment in the frontal plane. Strengthening of the hip abductors and adductors may be warranted as these muscles are known to be the major contributors to stability in this plane.

3. All strategies had the desired effect of greater loading of the affected limb and centralization of the COP and COM at seat-off in the frontal plane. Further investigation of all strategies is warranted to determine the impact of training with the CIM strategies on STS performance.
7.4 Future Research

Recommendations for additional research have emerged from the investigation of STS performance in people with stroke and the effect of CIM strategies on STS performance. Areas of future research are outlined below.

1. The minimal detectable difference (MDD) values for measures of balance in people with stroke obtained in this study appeared high, which may be due to heterogeneity of group scores. Further investigation of MDD values is warranted to establish values based on the participant’s baseline functional level.

2. One possible explanation for increased COP displacement in the frontal plane is weak hip abductor and adductor muscles. Further investigation of hip abductor/adductor strength and the relationship with COP displacement during STS performance in people with stroke is warranted.

3. A natural next step following study four is a randomized controlled trial (RCT) investigating the effect of STS training with the asymmetrical foot position strategy compared to STS practice without use of the CIM strategies. The asymmetrical foot position strategy is suggested for inclusion in a RCT for the following reasons: it does not require the purchase of additional equipment, all but one participant was able to perform the STS with the quart foot condition and this strategy would allow participants to start with the quart foot position and progress to the half foot position if unable to start with the half foot condition. Practice with one of the asymmetrical foot position strategy may lead to greater symmetry of weight-bearing and centralization of the COP and COM during STS at critical point of seat-off. Recommended measures of impairment include affected limb weight-bearing, total frontal plane displacement of the COP and COM and position of the COP and COM in the frontal and sagittal plane at seat-off. Recommended measures of function include gait speed and the five-times-sit-to-stand test. It is also suggested that a measure of balance confidence and participation be included. A follow-
up is recommended to measure retention of changes to STS performance and obtain a history of falls in the six months following training.

**7.5 Conclusions**

Findings from this body of research have contributed to knowledge of describing STS performance in people with stroke, and the reliability of measures of STS performance in people with stroke and healthy adults. In addition, the findings have expanded knowledge of the differences in STS performance between healthy adults and people with stroke and potential strategies used to complete the STS task in this clinical population. Furthermore, the findings have provided a greater understanding of the effect of CIM strategies used to alter STS performance in people with stroke.

**7.6 References**


Appendix A

Research Ethics Board Approval

QUEEN’S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

August 3, 2010

Ms. Charla Gray
School of Rehabilitation Therapy
Louise D. Acton Building
Queen’s University

Dear Ms. Gray,

Study Title: Reliability of sit-to-stand measures and effect of therapeutic strategies of these measures in healthy older adults and people with stroke

Co-Investigators: Dr. Elsie Culham

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol and consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair’s signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following list of ethics requirements you must fulfill over the course of your study:

➢ Reporting of Amendments: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. (see http://www.queensu.ca/vpr/reb.htm).

➢ Reporting of Serious Adverse Events: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information.

➢ Reporting of Complaints: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

➢ Annual Renewal: Prior to the expiration of your approval (which is one year from the date of the Chair’s signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

[Signature]
Chair, Research Ethics Board

Date

Study Code: REH-476-10

➢ Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete.
Appendix B

Letter of information and consent form

Title of Project: Reliability of sit-to-stand measures and effect of therapeutic strategies on these measures in healthy older adults and people with stroke.

Aim of the study:
You are being invited to participate in a research study by Charla Gray, PhD candidate in the School of Rehabilitation Therapy at Queen’s University. The purpose of this study is to determine the consistency of measures of balance and weight-bearing during a single test session and across two days of testing in a group of healthy older adults and people with stroke. In addition, this study will examine the effects of therapeutic techniques on measures of balance and weight-bearing when rising to stand from sitting. This study has been reviewed for ethical compliance by the Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board.

Eligibility for participation:
You are eligible to participate as a healthy older adult if you do not have any known balance disorders or any known orthopaedic or neurological conditions affecting your legs. You are eligible to participate as a subject with stroke if you had a stroke greater than six months previously, your stroke only affected one side of your body, it is your first stroke, and you have no other known orthopaedic or neurological conditions affecting your legs.

Description of visits and tests to be performed as part of the study:
Two visits to the Motor Performance Laboratory in the Louise D Acton Building, Queen’s University will be required for your participation in this study. The time required during each visit is approximately three hours.
Your height, weight, and foot length will be measured and recorded. In addition, you will be asked questions about your health with specific reference to history of diabetes, neurological disease, vision loss and medications that you are currently taking. The investigator will also record which leg you would use to kick a soccer ball. If you are participating as a subject with stroke you will be asked to complete a short pen and pencil test prior to testing to assess your awareness of space on your affected side. You will be asked to change into shorts, a loose fitting t-shirt and a pair of comfortable shoes.
Next you will be seated on a chair adjusted to your height and each foot will be placed on a force platform with your knees bent to approximately 100 degrees. The investigator will place clusters of infrared light emitting sensors bilaterally on the top of your foot, mid lower leg, mid thigh and
on your lower back and neck region. Before and after testing a measure of your weight distribution will be collected while you stand in a relaxed position with each foot on one of the two forceplates. At the beginning and end of the session you will be asked to stand-up from sitting three times without using your arms at a comfortable speed while looking at a target on the wall in front of you. Between these two tests you will be asked to stand-up from sitting three times using four different block heights placed under your dominant or unaffected foot, two different foam blocks under your dominant or unaffected foot and with two different foot positions with your dominant or unaffected foot placed ahead of your non-dominant or affected foot. Practice trials will be provided before testing each set-up to provide familiarity with the task. At the end of the session, the investigator will place a probe on specific bony landmarks to identify the location of these landmarks using the motion analysis software as you stand in a comfortable position.

**Risks/Side-Effects:**
There is a potential for falling during the task of rising to stand from sitting. A laboratory assistant will be beside you at all times during testing to help you regain your balance should you feel unsteady. You may also become tired during testing, you will be offered frequent seated rest periods and you may request them as needed. Juice and water is available during testing. You may experience some redness and irritation of your skin under the tape placed on your legs and neck but this should subside within a few hours of testing.

**Benefits:**
While you may not benefit directly from this study, results from this study will provide information to aid in the design of future studies to determine the effectiveness in improving balance and function in people who have had a stroke.

**Exclusions:**
You will not be able to participate in this study as a healthy older adult if you have any known prior history of traumatic brain injury, stroke or neurological impairments, or an orthopaedic or neurological condition affecting your legs. You will not be able to participate in this study as a subject with stroke if your stroke occurred in the last six months, it is your second stroke, it affected both sides of your body, you have lack of awareness of space on your affected side or you have an orthopaedic or neurological condition, other than your stroke, affecting your lower limbs.

**Confidentiality:**
All information obtained during the course of this study is strictly confidential and your anonymity will be protected at all times. You will be identified in any records using a subject
number only. Data will be stored in a filing cabinet and will be available only to the investigator (Charla Gray), fourth year Health Science student (Kai Yan ‘Grace’ Lui) and the faculty advisor (Dr. Elsie Culham). You will not be identified in any reports, publications or educational material that is developed based on this work.

**Voluntary nature of study/Freedom to withdraw or participate:**

Your participation in this study is voluntary. You may withdraw from this study at any time and your withdrawal will not have any consequences to you now or in the future. Your data will be removed from the analysis if you wish for it to be withdrawn.

**Liability:**

In the event that you are injured during your participation in this study, appropriate first aid and management advice will be provided and access to medical care, if necessary, will be arranged. By signing this consent you do not waive your legal rights nor release the investigators from their legal and professional responsibilities.

**Subjects Statement and Signature Section:**

I have read and understand the consent form for this study. I have had the purposes, procedures and technical language of this study explained to me. I have been given sufficient time to consider the above information and to seek advice if I chose to do so. I have had the opportunity to ask questions which have been answered to my satisfaction. I am voluntarily signing this form. I will receive a copy of this consent form for my information.

If at any time I have further questions, problems or adverse events, I can contact

Charla Gray at 613 533-6000 x77850

Or

Chair Rehabilitation Science Program Dr. Linda McLean at 613 533-6101

If I have questions regarding my rights as a research subject I can contact

Dr. Albert Clark, Chair, Queen’s University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board at (613) 533-6081

By signing this consent form, I am indicating that I agree to participate in this study.
STATEMENT OF INVESTIGATOR:

I, or one of my colleagues, have carefully explained to the subject the nature of the above research study. I certify that, to the best of my knowledge, the subject understands clearly the nature of the study and demands, benefits, and risks involved to participants in this study.
Appendix C

Single letter cancellation test


Scoring: The score is calculated by subtracting the number of H’s that were not crossed out from the total number of H’s (104); higher scores indicate a better performance. Unilateral spatial neglect can be inferred by examining the frequency of errors to the left or right of the middle of the page.
Appendix D

Within and between day reliability of novel outcome measures in people with stroke and healthy adults

Table D1: F and p values for ANOVAs performed on within day (day1 and day2) displacement measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (8,2)</td>
<td>p</td>
</tr>
<tr>
<td>MLCOM_mid</td>
<td>2.85</td>
<td>.09</td>
</tr>
<tr>
<td>MLCOP_mid</td>
<td>1.87</td>
<td>.17</td>
</tr>
<tr>
<td>MLCOM_COP</td>
<td>1.98</td>
<td>.17</td>
</tr>
</tbody>
</table>

Abbreviations: MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.

Table D2: Mean (SD), ICC and SEM values for within day (day1 and day2) displacement measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) (cm)</td>
<td>ICC</td>
</tr>
<tr>
<td>MLCOM_mid*</td>
<td>1.15(1.52)</td>
<td>.83</td>
</tr>
<tr>
<td>MLCOP_mid*</td>
<td>0.54(2.55)</td>
<td>.92</td>
</tr>
<tr>
<td>MLCOM_COP*</td>
<td>0.69(0.35)</td>
<td>.36</td>
</tr>
</tbody>
</table>

* n=9. Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.
Table D3: F and p values for ANOVAs performed on within day (day1 and day2) displacement measures in people with stroke

<table>
<thead>
<tr>
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<th>Day 2</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>APCOM_mid</td>
<td>1.67</td>
<td>.22</td>
<td>2.62</td>
<td>.10</td>
</tr>
<tr>
<td>APCOP_mid</td>
<td>.15</td>
<td>.86</td>
<td>4.01</td>
<td>.04</td>
</tr>
<tr>
<td>APCOM_COP</td>
<td>.68</td>
<td>.52</td>
<td>2.97</td>
<td>.08</td>
</tr>
<tr>
<td>APCOPa</td>
<td>.35</td>
<td>.72</td>
<td>1.99</td>
<td>.17</td>
</tr>
<tr>
<td>APCOPu</td>
<td>.48</td>
<td>.63</td>
<td>4.42</td>
<td>.03</td>
</tr>
</tbody>
</table>

Abbreviations: APCOM_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.
Table D4: Mean (SD), ICC and SEM values for within day (day 1 and day 2) displacement measures in people with stroke

<table>
<thead>
<tr>
<th>Measure</th>
<th>Mean (SD)</th>
<th>ICC</th>
<th>SEM</th>
<th>Mean (SD)</th>
<th>ICC</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>APCOM_mid*</td>
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<td>.95</td>
<td>1.02</td>
<td>-9.11(3.29)</td>
<td>.94</td>
<td>1.16</td>
</tr>
<tr>
<td>APCOP_mid*</td>
<td>0.54(2.01)</td>
<td>.89</td>
<td>1.28</td>
<td>.47(2.42)</td>
<td>.91</td>
<td>1.32</td>
</tr>
<tr>
<td>APCOM_COP*</td>
<td>-8.81(2.40)</td>
<td>.93</td>
<td>1.16</td>
<td>-9.20(3.43)</td>
<td>.96</td>
<td>1.14</td>
</tr>
<tr>
<td>APCOPa*</td>
<td>2.51(5.33)</td>
<td>.98</td>
<td>1.39</td>
<td>1.99(5.09)</td>
<td>.97</td>
<td>1.43</td>
</tr>
<tr>
<td>APCOPu*</td>
<td>-2.15(2.02)</td>
<td>.83</td>
<td>1.43</td>
<td>-1.81(2.22)</td>
<td>.87</td>
<td>1.48</td>
</tr>
</tbody>
</table>

* n=9. Abbreviations: APCOM_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.

Table D5: F and p values for ANOVAs performed on within day (day 1 and day 2) displacement measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>F (9,2)</th>
<th>p</th>
<th>F (9,2)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCOM_mid</td>
<td>.34</td>
<td>.71</td>
<td>.22</td>
<td>.81</td>
</tr>
<tr>
<td>MLCOP_mid</td>
<td>.49</td>
<td>.62</td>
<td>.59</td>
<td>.57</td>
</tr>
<tr>
<td>MLCOM_COP</td>
<td>.82</td>
<td>.46</td>
<td>.46</td>
<td>.64</td>
</tr>
</tbody>
</table>

Abbreviations: MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.
Table D6: Mean (SD), ICC and SEM values for within day (day1 and day2) displacement measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) (cm)</td>
<td>ICC (cm) SEM (cm)</td>
</tr>
<tr>
<td>MLCOM_mid</td>
<td>.37(.82) .63 1.01</td>
<td>.58(1.28) .87 .82</td>
</tr>
<tr>
<td>MLCOP_mid</td>
<td>.26(.51) .39 .92</td>
<td>.15(.96) .79 .83</td>
</tr>
<tr>
<td>MLCOM_COP</td>
<td>.53(.33) .17 .80</td>
<td>.79(.57) .67 .66</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.

Table D7: F and p values for ANOVAs performed on within day (day1 and day2) displacement measures in healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (9,2) p</td>
<td>F (9,2) p</td>
</tr>
<tr>
<td>APCOM_mid</td>
<td>.01 .99</td>
<td>.56 .58</td>
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<td>APCOP_mid</td>
<td>3.74 .05</td>
<td>2.75 .09</td>
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<tr>
<td>APCOM_COP</td>
<td>1.47 .26</td>
<td>1.17 .33</td>
</tr>
<tr>
<td>APCOPa</td>
<td>2.83 .09</td>
<td>1.08 .36</td>
</tr>
<tr>
<td>APCOPu</td>
<td>3.35 .06</td>
<td>3.94 .04</td>
</tr>
</tbody>
</table>

Abbreviations: APCOM_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.
The table below shows the mean (SD), ICC and SEM values for within day (day 1 and day 2) displacement measures in healthy adults.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Day 1</th>
<th>Day 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (SD) (cm)</td>
<td>ICC (cm)</td>
</tr>
<tr>
<td>APCOM_mid</td>
<td>-9.33(0.81)</td>
<td>.54</td>
</tr>
<tr>
<td>APCOP_mid</td>
<td>-0.23(1.26)</td>
<td>.83</td>
</tr>
<tr>
<td>APCOM_COP</td>
<td>-9.10(1.73)</td>
<td>.79</td>
</tr>
<tr>
<td>APCOPa</td>
<td>-1.16(1.38)</td>
<td>.78</td>
</tr>
<tr>
<td>APCOPu</td>
<td>-1.18(1.41)</td>
<td>.82</td>
</tr>
</tbody>
</table>

Abbreviations: ICC=intraclass correlation coefficient, SEM=standard error of the measurement, APCOM_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.
Table D9: F and p values for ANOVAs performed on between day displacement measures in people with stroke and healthy adults

<table>
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<tr>
<th>Measure</th>
<th>CVA</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F (8,1)</td>
<td>p</td>
</tr>
<tr>
<td>MLCOM_mid</td>
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</tr>
<tr>
<td>MLCOP_mid</td>
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<td>.94</td>
</tr>
<tr>
<td>MLCOM_COP</td>
<td>1.11</td>
<td>.32</td>
</tr>
</tbody>
</table>

Abbreviations: CVA=participant with stroke, HA=healthy adult, MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.

Table D10: ICC, SEM, MAD (SD) and MDD values for between day displacement measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA</th>
<th>HA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICC</td>
<td>SEM</td>
</tr>
<tr>
<td></td>
<td>(cm)</td>
<td>(cm)</td>
</tr>
<tr>
<td>MLCOM_mid</td>
<td>.88</td>
<td>.80</td>
</tr>
<tr>
<td>MLCOP_mid</td>
<td>.94</td>
<td>.61</td>
</tr>
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<td>MLCOM_COP</td>
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<td>.65</td>
</tr>
</tbody>
</table>

*n=9. Abbreviations: CVA=participant with stroke, HA=healthy adults, ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MAD=mean absolute difference, MDD=minimal detectable difference, MLCOM_mid=centre of mass position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOP_mid=centre of pressure position in the frontal plane at seat-off relative to the midpoint between the two malleoli, MLCOM_COP=absolute distance between the centre of mass and centre of pressure position at seat-off.
Table D11: F and \( p \) values for ANOVAs performed on between day displacement measures in people with stroke and healthy adults

<table>
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<tr>
<th>Measure</th>
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<th>( p )</th>
<th>HA</th>
<th>( F ) (9,1)</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>APCOM_mid*</td>
<td>.96</td>
<td>.36</td>
<td>2.93</td>
<td>.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>APCOP_mid*</td>
<td>12.72</td>
<td>.01</td>
<td>9.13</td>
<td>.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>APCOM_COP</td>
<td>.22</td>
<td>.65</td>
<td>.03</td>
<td>.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>APCOPa*</td>
<td>2.59</td>
<td>.15</td>
<td>11.2</td>
<td>.01</td>
<td></td>
<td></td>
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<tr>
<td>APCOPu*</td>
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<td>.35</td>
<td>4.86</td>
<td>.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*df (8,1). Abbreviations: CVA=participant with stroke, HA=healthy adult, APCOM\_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP\_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM\_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.
Table D12: ICC, SEM, MAD (SD) and MDD values for between day displacement measures in people with stroke and healthy adults

<table>
<thead>
<tr>
<th>Measure</th>
<th>CVA</th>
<th>HA</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>.58</td>
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<td>1.17(1.03)</td>
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*n=9. Abbreviations: CVA=participant with stroke, HA=healthy adults, ICC=intraclass correlation coefficient, SEM=standard error of the measurement, MAD=mean absolute difference, MDD=minimal detectable difference, Abbreviations: APCOM_mid=centre of mass position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOP_mid=centre of pressure position in the sagittal plane at seat-off relative to the midpoint between the malleoli, APCOM_COP=absolute distance between the centre of mass and centre of pressure at seat-off in the sagittal plane, APCOPa=distance between the affected limb centre of pressure and the medial malleoli of the affected limb at seat-off, APCOPu=distance between the unaffected limb centre of pressure and the medial malleoli of the unaffected limb at seat-off.
Appendix E

Effect of strategies for individual participants

Figure E1: Distance between the COP position and midpoint between the malleoli in the frontal plane (MLCOP_mid) at seat-off for each participant with the baseline and solid block conditions.

SB1=2.54cm block, SB2=5.08cm block, SB3=7.62cm block, SB4=10.16cm block.
Figure E2: Distance between the COP position and midpoint between the malleoli in the frontal plane (MLCOP_mid) at seat-off for each participant with the baseline and compliant block conditions.

CB1=2.72kg compliant block, CB2=6.63kg compliant block.
Figure E3: Distance between the COP position and midpoint between the malleoli in the frontal plane (MLCOP_Midline) at seat-off for each participant with the baseline and quart-foot condition.

The graph shows the distance (in cm) between the COP position and the midpoint between the malleoli in the frontal plane for each participant (CVA01 to CVA15). The condition is depicted along the x-axis, with baseline and quart conditions. The y-axis represents the distance in cm.

The quart condition indicates the unaffected limb placed a quart foot length ahead of the affected limb.
Figure E4: Distance between the COM position and midpoint between the malleoli in the frontal plane (MLCOM_mid) at seat-off for each participant with the baseline and solid block conditions.

SB1=2.54cm block, SB2=5.08cm block, SB3=7.62cm block, SB4=10.16cm block.
Figure E5: Distance between the COM position and midpoint between the malleoli in the frontal plane (MLCOM_mid) at seat-off for each participant with the baseline and compliant block conditions.

CB1=2.72kg compliant block, CB2=6.63kg compliant block.
Figure E6: Distance between the COM position and midpoint between the malleoli in the frontal plane (MLCOM_mid) at seat-off for each participant with the baseline and quart-foot condition.

quart=unaffected limb placed a quart-foot length ahead of the affected limb.
Figure E7: Distance between the COM position and midpoint between the malleoli in the sagittal plane (APCOM_mid) at seat-off for each participant with the baseline CB1 and CB2 condition.

CB1=2.72kg compliant block, CB2=6.63kg compliant block
Figure E8: Distance between the COM position and midpoint between the malleoli in the sagittal plane (APCOM_mid) at seat-off for each participant with the baseline quart-foot and half-foot condition.

quart=unaffected limb placed quart-foot length ahead of the affected limb
half=unaffected limb placed half-foot length ahead of the affected limb
Figure E9: Distance between the COM and COP position in the sagittal plane (APCOM_COP) at seat-off for each participant with the baseline and quart-foot condition.

quart=unaffected limb placed quart-foot length ahead of the affected limb
Figure E10: Distance between the COM and COP position in the sagittal plane (APCOM_COP) at seat-off for each participant with the baseline and half-foot condition.

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half=unaffected limb placed half-foot length ahead of the affected limb