Trunk inter segmental coordination during gait

in post stroke individuals.

Revital Regina Hacmon
BPT

School of Physical and Occupational Therapy
McGill University
Montreal, Quebec
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DEDICATION

Coming to Canada and completing this Master's degree was inspired by one very special person – Jacqueline Reznik. Jackie, this thesis is dedicated to you! You have been a part of my life for more than 10 years, since the first course you taught me at the physiotherapy school, then through working with you and having you as my mentor, and now as my best friend. Thank you for being how you are to me: First for taking me under your wings and giving me tools to learn, develop and succeed. Then you challenged me and made me believe that nothing is impossible. Thank you for all of that and more.

Also I want to dedicate this work to all my family. Despite being thousands of miles away from me, you were the best support I could wish for. To my friends here in Montreal that helped me feel at home. And last but not least I want to thank Hagay – thank you for your patience, tolerance, support and for the long wait. You have no idea how much it has meant to me.

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PREFACE

This thesis is organized in a manuscript-based format in accordance with the guidelines of the Faculty of Graduate and Postdoctoral Studies of McGill University and features one research manuscript.

Chapter 1 introduces the topic and the objectives of the study.

Chapter 2 presents a review of the literature relevant to the area of study.

Chapter 3 describes the methodology in greater detail than offered in the manuscript to follow.

Chapter 4 Research manuscript: "Deficits in trunk coordination during comfortable-speed walking are related to clinical balance and gait function in chronic stroke"

Chapter 5 summarizes the study's main findings as well as the clinical significance and future directions.

Chapter 6 provides the list of references contained within the thesis and appendices.

CONTRIBUTION OF AUTHORS

The manuscript that is contained in this thesis is entitled: "Deficits in trunk coordination during comfortable-speed walking are related to clinical balance and gait function in chronic stroke". The work for this manuscript was done under the supervision of Dr. Mindy F. Levin and took place at the Virtual Reality and Mobility Laboratory at the Center for Interdisciplinary Research in Rehabilitation, Feil and Oberfeld JRH/ CRIR Research Center, Jewish Rehabilitation Hospital, Laval, Quebec, Canada. Dr. Levin and I contributed to the entire project over all the stages: from conception of the research hypothesis, design of the study protocol and interpretation of the results. Dr. Lamontagne (as a member of my supervisory committee and the head of the Virtual Reality and Mobility Laboratory) provided the laboratory in which the data was collected and participated in the interpretation of the results and preparation of the manuscript. Tal Krasovsky collaborated in the data collection and results analysis. I was involved in all data collection sessions and was responsible for the data processing, data analysis, statistical analysis, writing of the manuscript and thesis presented here.

STATEMENT OF ORIGINALITY

I attest to the fact that this thesis contains no material previously published or written by another person, except where references are made.

Elements of this Master's thesis provide original contributions to the understanding of trunk coordination and its relationship with gait and balance performance in chronic stroke.

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LIST OF ABBREVIATIONS

ABC	Activities-Specific Balance Confidence Rating Score
ADL	Activity Of Daily Living
CM	Chedoke-Mcmaster Impairment Inventory
CNS	Central Nervous System
CRIR	Center of Interdisciplinary Research in Rehabilitation
CRP	Continuous Relative Phase
DGI	Dynamic Gait Index
FGA	Functional Gait Assessment
ICF	International Classification of Functioning, Disability and Health
JRH	Jewish Rehabilitation Hospital
LBP	Low back pain
PASS-TC	Postural Assessment Scale for Stroke Patients
PD	Parkinson's disease
pl	Pelvis
PNF	Proprioceptive Neuromuscular Facilitation
PPP	Pregnancy-related pain in the pelvis
ROM	Range of motion
TCT	Trunk Control Test
th	Thorax
TIS	Trunk Impairment Scale
TUG	Timed Up and Go Test

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ABSTRACT

People who have had a stroke have difficulty walking. One approach that physiotherapists use to improve walking after a stroke is training people to have better control over the movements of their trunk at the shoulder and hip levels. While previous research has shown that people with low back pain and Parkinson's disease have disruptions in the production of rhythmical thoracic and pelvic movements (inter segmental coordination) while walking, there is a lack of information related to this deficit in people who have had a stroke. The aim of this study was to measure: 1) the level of inter-segmental coordination between movement of thoracic and pelvic trunk segments during locomotion in people with stroke and 2) to examine if there are correlations between the level of inter-segmental coordination and gait and balance scores of the participants. Eleven individuals with stroke and 11 age-matched healthy controls participated in the 2 sessions of the study: 1) clinical evaluation: BesTest (clinical balance scale) and the Functional Gait Assessment (FGA) for all subjects and Chedoke-McMaster (CM) only in the stroke group. 2) Kinematic evaluation: Gait kinematic were recorded during self-paced treadmill walking at 2 different speeds in 2 planes (yaw and roll). The angular movements of the thorax and the pelvis and the continuous relative phase between them (CRP) were measured and compared between groups. Correlation analysis was conducted to identify the strength of the relationships between the clinical and kinematic data. Results showed that, at comfortable speed, individuals with stroke had reduced inter-segmental coordination in the yaw plane and that this reduction was correlated with

functional levels. This information may be useful for physiotherapists to design more effective treatment programs to improve locomotor ability in people post-stroke.

ABREGÉ

Les gens qui subissent un accident vasculaire cérébral (AVC) ont de la difficulté à marcher. Une approche utilisée par les physiothérapeutes pour amender la marche est un entraînement servant à améliorer le contrôle des mouvements du tronc au niveau des épaules et des hanches. Des recherches précédentes ont démontré que les gens avec des maux de dos et la maladie de Parkinson ont des disruptions dans la production des mouvements rythmiques du thorax et du bassin (coordination inter-segmentale) durant la marche, mais il y a un manque d'information regardant ce déficit dans les gens ayant subi un AVC. Le but de cette étude était de mesurer : 1) le niveau de coordination inter-segmentale entre les mouvements des segments du thorax et du bassin pendant la locomotion des gens atteint d'un AVC et 2) d'examiner s'il existe une corrélation entre les niveaux de coordination inter-segmentale et les scores d'équilibre et de démarche des participants. Onze individus avec un AVC et onze participants contrôles d'un âge similaire ont participé dans les deux sessions de l'étude : 1) évaluation clinique : BesTest (échelle clinique d'équilibre) et le test de démarche fonctionnel (FGA) pour tous les sujets et le Chedoke-McMaster (CM) pour les sujets avec AVC seulement. 2) évaluation cinématique : les données cinématiques de la démarche ont été prises durant une marche sur tapis roulant à une vitesse choisie par l'individu, à deux vitesses différentes et sur deux plans ('yaw' et 'roll'). Les mouvements angulaires du thorax et du bassin ainsi que la phase continue et relative entre les deux (CRP) ont été mesurés et comparés entre les groupes. Une analyse de la corrélation a été réalisée pour identifier la force de la relation entre les mesures

cliniques et cinématiques. Les résultats démontrent qu'à une vitesse confortable, les individus ayant eu un AVC avaient moins de coordination inter-segmentale dans le plan 'yaw' et que ce déclin avait une corrélation avec les niveaux fonctionnels. Cette information peut être utile pour aider les physiothérapeutes à mettre en place des programmes de traitements plus efficaces pour améliorer les habiletés locomotives auprès de la population ayant subi un AVC.

CHAPTER 1: INTRODUCTION

1.1 Overview

A stroke is a situation in which there is an interruption of the supply of oxygen and nutrients to the brain, usually because of a blockage of one of more brain blood vessels or by hemorrhage. This situation causes damage to the brain tissue which may lead to cell death (infarction) at the lesion site.[1] Symptoms of stroke can occur and affect all levels of health and health-related domains as described by the World Health Organization's International Classification of Functioning, Disability and Health (ICF) model (Body Structure/ Function, Activity, Participation and Environmental and Personal factors). At the Body Structure/ Function level it can affect motor, sensory, cognitive, perceptual, balance control, language, emotional etc.; at the Activity level, stroke can affect transfers, walking ability, upper limb function etc.; at the Participation level, stroke affects community ambulation and outdoor activities. In addition, Environmental and Personal factors may have an effect on the severity of the stroke and the outcome of rehabilitation. The effect and the relationship between stroke and all ICF levels make stroke one of the leading causes of disability worldwide.[2] Stroke impacts more than the individual himself. Stroke affects the family and the society. Family members have to act as care-givers which require a change in lifestyle and sometimes even a loss of income. In addition, the cost to the health care system related to stroke is very high. For example, in Canada the cost every year is estimated to be $2.7 billion.[3]

In Canada, more than 50,000 strokes occur each year and about 300,000 Canadians are living with the effects of stroke. From all the people who have a stroke, 40% are left with a moderate to severe impairment and 10% are so severely disabled that they require long-term care.[4] Deficits in mobility are common in chronic stroke patients. At the end of the rehabilitation period, most individuals with stroke can walk independently [5] but with a speed and endurance that is insufficient to function effectively in the community.[6,7]

CHAPTER 2.0: LITERATURE REVIEW

2.1 Kinematic deficits in gait following stroke

Walking, or gait, is one of the common functions with which individuals post stroke have deficits. The deficits can range from a complete inability to walk to different abnormal walking patterns such as asymmetry between the extremities, changes in weight bearing on the lower extremities, changes in gait speed as well as in other distance and temporal gait factors. The abnormality in gait can be described using different methods, such as kinematics, kinetics, muscle activity and the response to a change in the environment or the walking surface. This thesis project discusses one of the kinematic variables that are related to motor coordination deficits between trunk segments: the thorax and the pelvis and its effect on gait.

2.1.1 Gait speed and endurance

In general, at the end of the rehabilitation program in the hospital, the majority of individuals post stroke can walk independently[8], but with a slower speed than healthy individuals of the same age group.[5] In addition, they could not maintain a comfortable walking speed and walked a significantly smaller distance compared to healthy subjects.[6,9] Function in the community requires a specific gait speed that is measured by the ability to cross a street in a small city at minimum gait speed of 0.8m/s.[10,11] Studies have shown that the speed and endurance of most individuals with stroke are not insufficient to function effectively in the community.[6,7] A commonly used test for gait endurance is the 6 minute walk test (measuring the distance a person is able to walk for six minutes with recorded rest stops). It has been found that individuals with stroke use between 50-67% more metabolic energy than healthy control subjects walking at the same gait speed, which may be associated with lower endurance in the stroke group.[12] Slow gait was also associated with poor motor control and weakness of the lower extremity.[13]

2.1.2 Distance and temporal gait factors

Distance and temporal gait factors are common tools to evaluate the severity of motor involvement related to gait after stroke. Although there are some variables that affect these factors (i.e. gait speed, time of stroke onset, the stage of the general clinical recovery of the patient from the stroke, etc.), some of the factors have been well studied. The main deficits of gait distance factors in post stroke subjects for the affected limb are shorter stride length, wider step and bigger toe-out angle compared to limbs of healthy subjects and the less affected limb. Related to temporal factors stroke patients have longer stride time, lower cadence, change in the stance/swing ratio between limbs, longer swing time in the affected limb and longer stance time in the less affected limb.[12,14-16]

2.1.3 Joint kinematics

The norms of joint ranges of motion during the different phases of the gait cycle are well known. It has been shown that individuals post stroke have some abnormalities of joint range of motion of the affected side in all planes.[12-14]

Hip: during the stance phase, hip flexion ROM can be normal or lower than healthy subjects. When extension is needed, mainly in late stance and for the push off phase, it is common to find reduced hip extension in this group of subjects. There are cases in which the hip is flexed at toe-off (the terminal part of the stance).[12-14] During the swing phase, limited hip flexion is common.[12]

Knee: During the stance phase, three patterns at the knee are commonly observed post stroke: (1) increased knee flexion, (2) increased knee flexion followed by hyperextension in late stance, delayed movement into knee flexion and reduced knee flexion at toe-off, (3) increased hyperextension during for all/ most of the stance phase.[12-14] During the swing phase, it is common to observe a lack or decrease of knee flexion range of motion.[12]

Ankle: Two main patterns of ankle movement occur during the stance phase: (1) initial ground contact with a flat foot with a decreased range of dorsiflexion during mid-stance and push off: or (2) increased plantar flexion during the whole stance phase, both usually followed by decreased dorsiflexion/ plantar flexion.[12-14]

A few studies also describe the behavior of the arms and the trunks in hemiplegic gait: the arms have smaller amplitude of movement, while the shoulders are slightly extended and the elbows are slightly flexed, compared to healthy controls. The trunk may be flexed forward during the stance phase and some lateral shift appears during the stance phase of the less affected limb.[12-14]

2.2 Gait rehabilitation in stroke

The limitation in walking is one of the main reasons for decreased function and lack of participation for individuals with stroke. Therefore gait rehabilitation plays a large role in the rehabilitation of stroke.[6,7] Different approaches of neural rehabilitation have been developed to treat stroke. The three main principals of the different approaches are: (1) orthopedic based (during the 1940s)- related to muscle relaxation, minimizing excessive muscle contraction and achieving function through compensation with other parts of the body, (2) neurophysiological based (during the 1950s-1960s) such as Bobath, Rood and Proprioceptive Neuromuscular Facilitation-in these approaches the therapist is the main active "part" by moving the patient and giving resistance, (3) neuropsychology/ motor learning based (1980s). The patient is an active part in task-specific practice that is related to function to be achieved, while the therapist directs and give feedback.[17]

In the clinics today, physiotherapists use different techniques that conform to one or more of these approaches. A common classification of function scheme used today is the ICF[18] (International Classification of Functioning, Disability and Health) model which includes two main categories: health condition and contextual factors (environmental and personal). The health condition category includes:

*Body Function*s are physiological functions of body systems (including psychological functions.

*Body Structure*s are anatomical parts of the body such as organs, limbs and their components.

Activity is the execution of a task or action by an individual, while activity limitations are difficulties an individual may have in executing activities.

Participation is involvement in a life situation.[18]

Using the ICF model, it is clear that the different techniques address all the health condition levels:

Body Structure/function: strength training, functional electrical stimulation, biofeedback, splinting the lower extremity, soft tissue stretching.

Activity (walking ability): treadmill training, partial body-weight support treadmill training.

Participation (community ambulation): over ground walking, walking training on different surfaces/ directions/slopes and walking in different environments: shopping mall, around the house, crossing a road, etc.

All those approaches and techniques are well documented in the literature as affecting and helping improve gait, and still there is no evidence that one is better than the other.[17,19,20] Better understanding of the mechanisms involved in the development of gait deficits, may help when choosing the most appropriate treatment approach/technique for each patient.

2.3 Balance deficits following stroke

Balance is the ability to keep the body mass over the base of support under different task and environmental conditions.[21] The balance of the body is affected by internal mechanisms such as muscle strength, proprioception, visual, tactile and vestibular sensory inputs and external mechanisms related to the environment (noise, surface, wind etc.). To maintain balance under these conditions, the central nervous system (CNS) needs to support the body against external forces, to maintain the center of mass balanced over the base of support and to stabilize parts of the body while moving other parts.[22,23] Three aspects of balance can be evaluated: steadiness (the amount of sway), symmetry (symmetry of weight on the weight bearing components) and dynamic stability (moving without falling).[24] In post stroke patients, deficits in all the three aspects occur. Patients with stroke have greater postural sway,[25-27] asymmetry of weight bearing with greater weight-bearing on the less affected leg,[28-30] and decreased ability to move within a weight bearing posture without loss of balance.[31,32] A relationship was found between gait speed and balance, which indicated that balance deficits may be one of the reasons for decreased gait speed. [33,34]

2.4 Balance rehabilitation

Motor recovery and daily function after stroke are strongly related to balance impairments.[35] Therefore, balance rehabilitation is an important part of the rehabilitation program after stroke. Carr and Shepherd[19] offer simple intervention principals for balance rehabilitation post stroke:

- To work on balance of the body mass during voluntary actions in different positions.
- To practice the quick responses to predicted and unpredicted situations that may disturb balance.
- To prevent contractures at the joints, soft tissues and muscle shortening.
- To improve the body mass support by increasing muscle strength and coordination of the whole body and mainly of the lower limb extensors.

There are different techniques for balance rehabilitation such as group therapy, standing and sitting balance practice, motor relearning programs with a focus on balance during the accomplishment of the task, weight support training, force platform with visual feedback etc. As for gait retraining, there is no evidence of greater effectiveness of one technique over the other, but there is moderate evidence that balance training improves balance scores.[36]

2.5 Trunk control and performance in individuals post stroke

Trunk control is an important predictor of functional recovery after stroke.[37] Individuals with sub-acute and chronic stroke have lower levels of trunk performance compared to age-matched control groups.[38] Trunk performance is often measured using only parameters of muscle strength.[39,40] However, in a series of studies on the development of a clinical measure of trunk performance, the "Trunk Control Test", Verheyden and colleagues[41] defined trunk performance using parameters of muscle strength as well as performance of gross movements such as rolling, sitting up from lying and balance in sitting. Overall, such clinical scales of trunk performance measure task accomplishment but not how the task was accomplished or the quality of movement.

The two main clinical assessment tools that particularly evaluate trunk performance are the Trunk Control Test and the Trunk Impairment Scale. The Trunk Control Test (inter-rater reliability, Spearman, r=0.76) evaluates rolling, moving from supine to sitting and remaining in the seated position. The Trunk Impairment Scale (ICCs for test-retest and interrater reliability for subscale and total scale between 0.85 and 0.99) evaluates static and dynamic sitting balance and trunk coordination. Verheyden et al[41]. define trunk coordination as the ability to rotate the upper part of the trunk or the lower part of the trunk symmetrically to both the healthy and the paretic sides. Strong relationships between trunk performance and balance, gait and functional ability indicate that both scales are good clinical assessment tools.[40] For the trunk coordination test, there is a specific timing requirement for the performance of the task (e.g., to rotate the upper trunk 6 times, each shoulder should be moved forward 3 times within 6 s). These tests however, focus on coordination during sitting and not during gait and provide us with information related to the accomplishment but not to the quality of the task. A study by Hsieh et al.[42] found a relationship between trunk control performance (using the Postural Assessment Scale for Stroke Patients, PASS-TC) and comprehensive ADL testing (activity of daily living). They found that the level of trunk control at an early evaluation stage in stroke patients can predict the level of the ADL 6 months after the stroke: the lower the score of the PASS-TC, the lower the ADL performance.

For a better understanding of the relationship between deficits of the trunk and gait function, measurements that evaluate the quality of trunk movements are needed. Using tools and measures that assess trunk movements may help therapists choose the most appropriate treatment to improve trunk and gait function.

2.6 Relationship between thoracic and pelvic segmental movements in healthy subjects

During the last century, research has been done in order to achieve a better understanding of the role of the pelvis and thorax movements and the relationship between them in human gait. One of the first studies in the field found that the pelvis movements play an important role in the definition of normal gait:

(1) Axial rotation is needed to decrease the total range of motion of the center of mass and to increase the step length, (2) side flexion movements smooth the gait and help to decrease the total range of motion of the center of mass and (3) flexion- extension movements help keep the movement smooth.[43] Stokes et al[44] studied the thorax-pelvis relationship during gait and found that during most of the gait cycle the thorax and the pelvis rotated in a contra-lateral direction (anti-phase). They suggested that this pattern helps to reduce the rotational momentum of the body and helps to achieve smoother gait.

Van Emmerik and Wagenaar[45] studied the effects of walking velocity on the dissociation between movements of the thorax and pelvis (inter-segmental dissociation) using the continuous relative phase (CRP) measure. CRP is a measure of the coordination between thorax and pelvic rotations during the entire stride or set of strides. The range of CRP, between 0º to 180º reflects the degree of the in-phase to anti-phase relationship respectively between the segments studied. By definition, 0º represents a phase of in-phase, 180º a phase of anti-phase and the values between them are out of phase. They studied thoracic and pelvic rotations limited to the transverse plane (yaw plane; rotation movements), probably because this is the plane with the most movement during gait. Total range of motion of each of the segments was calculated as the distance from maximum to a minimum rotation in every stride. Trunk rotation range, or the angular difference between the two segments, was obtained by subtracting the time series of the rotation movement of the pelvis from that of the thorax, and then calculating the maximal difference between peaks and valleys of the resulting signal for each stride cycle. The CRP increased with increasing walking speed. At low speed (0.3 m/s) the

CRP value was about 25º (closer to in-phase) and at higher speed (1.3 m/s), it was 110º (closer to anti-phase). The range of motion of the pelvis and thorax rotations depended on gait speed. With decreasing gait speed, range of motion of all three rotations was larger compared to the same speeds during walking while increasing gait speed.

Speed dependence was supported by findings of Bruijn et al.[46]and Lamoth et al.[47] A study by Van Emmerik and colleagues[48] compared the thorax-pelvis coordination at different speeds between different age groups (younger: 23.3±4; middle: 49.3±5.4; older: 72.6±3.8). They found the same behavior in all groups- the faster they walked, the more the coordination was in the direction of anti-phase. They also observed a difference related to age at high gait speeds: when the subjects walked at 1 m/s and higher, the values of the coordination for the older group were lower than the two younger groups, but still in the direction of anti-phase. Overall, there is a normal pattern of coordination in the healthy population: when healthy subjects walked at low gait speed, the inter-segmental coordination between the thorax and the pelvis in the transverse plane was in the in-phase pattern, but when speed was increased, the coordination pattern changed to anti-phase.

In the coronal plane (roll plane; side flexion movements) a similar speed effect has been observed, while in the sagittal plane (pitch plane; flexion-extension), the effect was opposite- the faster the subjects walked, the more an in-phase pattern occurred in that plane.[48]

2.7 Relationship between thoracic and pelvic segment axial rotation movements in different pathologies

Lamoth et al.[49] studied the effect of walking velocity on global trunk coordination. They analyzed the kinematics of thoracic, lumbar and sacral trunk segments in healthy subjects and in subjects with low back pain (LBP) using a 3D motion tracking system. They evaluated inter-segmental rotations in the transverse and coronal planes. In patients with LBP, range of motion of the thoracic, lumbar and pelvic segments did not differ from the healthy group despite differences in stride length. However, there were differences in the timing (phase relationships) between the thoracic and pelvic rotations in the transverse and the coronal planes and changes in their variability. In the transverse plane, at a comfortable gait velocity (LBP 0.91 m/s, Control 1.3 m/s) the relative phase between the thorax and the pelvis was smaller in the LBP compared to the control group. At higher walking speeds (1.05-1.66 m/s), the amount of transverse out-of-phase movement (counter-rotation) was less in the LBP group, but there was no significant effect of speed on the variability of the CRP across trials in this plane. Gait in healthy subjects was characterized by variability in the CRP across trials and changes in two walking speeds. However, patients with LBP tended to adopt a pattern of in-phase coordination between thorax and pelvis rotation across different walking speeds giving rise to a decrease in overall gait stability, which was defined in this study as a decrease in the amount of variability in the coordination patterns . In addition, recent study by Seay et al.[50] describes a difference in the coordination in LBP subjects in running. The study involved 3 groups; runners with LBP, runners who had recovered from LBP and runners with no history of LBP. They found that during running, the group with the LBP and the group with the history of LBP had more in-phase thorax-pelvis coordination in the transverse plane during the gait cycle compared to the controls. This finding suggests that even though CRP is speed dependent, different behaviors occur with different pathologies. The same coordination was studied on a group of women that had pregnancy-related pain in the pelvis (PPP). The results were in the same direction: the PPP group had lower maximum gait speeds. The control group had the typical behavior of in- phase coordination at slow speed, and changed the pattern in the direction of anti-phase with increasing gait speed. The PPP behavior was different- even though the direction of the pattern was in anti-phase with increasing speed, the values were significantly lower than the controls.[51] A study by Van Emmerik et al.[52] showed that individuals with Parkinson's disease (PD; n=27) had a significantly smaller relative phase between thorax and pelvis rotations in the transverse plane when walking at different speeds ranging from 0.2-1.4 m/s compared to a healthy age-matched control group. They calculated the CRP between the normalized phase angles of the thorax and pelvis. The relative phase variability was derived from the standard deviation of the relative phase over the entire stride cycle at each specific walking speed. PD patients had smaller relative phase values than controls, and in both groups, relative phase increased with increases in walking speed. The authors concluded that CRP may be a sensitive measure for early diagnosis and assessment of trunk movement coordination deficits in PD.

Only one group has evaluated thorax- pelvis coordination in the transverse plane and the effect of gait speed (ranges 0.25-1.5 ms^{-1}) on this coordination in stroke subjects.[53] In both, chronic stroke and healthy subjects, CRP, thorax and total trunk ROM values were linearly related to gait speed: the faster the subjects walked, the higher the CRP (more anti-phase) and total trunk ROM values. However, the pelvic ROM increased when speed increased only in the control group. Overall, stroke subjects did not differ from healthy controls in mean values of CRP, pelvis ROM and total ROM. However, stroke subjects used a greater thoracic ROM compared to controls.

Several studies have assessed kinematic changes during gait in different patients with pathologies and in stroke patients under different walking speed conditions, but no study has investigated the relationship between trunk coordination (e.g., CRP analysis) and gait or balance deficits in individuals with stroke, even though these deficits may be related to changes in inter-segmental coordination between the upper and lower parts of the trunk.

2.8 Rationale and objective

Gait rehabilitation to achieve better gait performance is an important part of stroke rehabilitation. Although there are many techniques and treatments for improving gait (muscle strengthening, biofeedback, functional electrical stimulation, proprioceptive neuromuscular facilitation (PNF), Bobath approach, treadmill training, partial body-weight support, etc.), there is no clear advantage of one technique over the other.[20,54] This suggests that there is still a need to better understand the mechanisms underlying gait disturbances in stroke patients in order to achieve better gait performance outcomes using the best techniques. The work presented in this thesis reports on the specific mechanism of trunk coordination that characterizes gait and the relationship between trunk rotation, gait and balance performance.

The objective of this study was to estimate the relationship(s) between inter-segmental coordination of thoracic and pelvic movements during locomotion and functional deficits related to gait and balance in individuals with chronic post-stroke hemiparesis.

We hypothesized that individuals with stroke would have deficits in inter-segmental coordination between thoracic and pelvic movements in the transverse plane during gait compared to healthy control subjects. We further hypothesized that individuals with stroke who have better inter-segmental trunk coordination would perform better on functional gait and balance measures.

CHAPTER 3: METHODS

3.1 Design

The study was a cross-sectional study with two groups: stroke patients and healthy control subjects who all participated in two sessions of two hours each.

3.2 Study population

Participants with stroke were recruited from hospital discharge lists, as well as through contact with therapists from institutions within CRIR. The inclusion criteria were: aged between 40-75 years; presence of a first unilateral ischemic stroke; residual walking ability (able to walk 10 steps without aid on a treadmill); residual arm movement (Chedoke-McMaster (CM) Arm Scale ≥3/7); impairment in postural control, as indicated by a score of ≤6/7 on the CM Impairment Inventory,[55] impairment in over ground walking speed (≤ 0.95 m/s). The exclusion criteria were: marked visuospatial neglect (Bells Test)[56] or visual field deficits and musculoskeletal disorders in the arms or legs (from medical chart). Recruitment letters explaining the nature of the study were sent to potential participants. People interested in participating contacted the research center. They were screened by research clinicians for compliance with inclusion and exclusion criteria prior to being asked to participate in the study. The content of the letter and recruitment process were approved by the Ethics Committee of CRIR.

Healthy active individuals aged between 40-75 years who had no history of neurological or musculoskeletal problems affecting the trunk and legs were invited to participate in the study. Healthy subjects were recruited from volunteers at the JRH (via a request to the head of the JRH volunteers), the JRH staff and relatives of the stroke subjects.

All subjects were fully informed of the procedures involved, and were asked to sign a consent form approved by the Ethics Committee of CRIR prior to their participation. Risks and advantages related to their participation were described in the consent form (Appendix V), and they were informed that it was possible to withdraw from the study at any time.

Sample size: The calculation of the sample size was based on data from Lamoth et al.[57] of the amount of trunk rotation in the transverse plane in groups of healthy subjects and subjects with LBP (healthy = 111° ± 19°; LBP = 71° ± 18°). According to our calculations done with statistical software GPower3[58], a sample size of 10 subjects per group would have an effect size of 1.1, with an α level of 0.05 and a power of 0.95 of rejecting a false null hypothesis. We recruited 12 subjects per group to allow for a rate of 20% drop out of the participants during the study. One subject in the stroke group did not attend the second session and the kinematic data of one healthy subject was missing due to a technical problem with the recording system. Eleven stroke and eleven healthy control subjects participated in the study (Table 1).

3.3 Data collection

Subjects walked on a self-paced motorized treadmill. To prevent falling, subjects wore a safety harness which was attached to the ceiling with a strong chain that allowed the subject to move over the length and width of the treadmill and still be attached safely with the harness. Treadmill speed was determined by the length of a cord attached to a pulley that was placed 1.88 m (when the subject stands at the middle of the treadmill) behind the subject and attached to the back of the harness. Safety switches were mounted on the treadmill and the control box that stopped the treadmill. When it was necessary for safety issues or any other reason to stop the treadmill, the treadmill could have been stopped by pressing one of the safety switches which turned off the power of the treadmill.

Subjects walked at their comfortable speed and as fast that they could without running (for stroke subjects) or slower in order to match the walking speed of the stroke subjects (for the controls). To minimize variability in walking speed, subjects followed the pacing of a metronome that was matched to their walking cadence. After becoming familiar with walking on the self-paced treadmill (between 2-5 min walking), participants were instructed to walk naturally in the middle of the belt of the treadmill. In addition, subjects wore a heart-rate monitor to ensure that heart rate remained at a sub-maximal effort (70% of 220 minus age) level in each trial.

Kinematic data were collected using a 12 camera high-resolution (~1 mm) Vicon-512™ system (using reflective markers and sampling rate of 120 Hz). The Vicon system is the gold standard for kinematic measurements of gait.[59] In post stroke subjects, for different kinematic measures in the sagittal plane, the system was found reliable to record movements both for between sessions and within sessions, between trials (ICCs of 0.82-0.99).[60] Thoracic and pelvic rotations in 2 dimensions: roll and yaw were recorded using clusters of 3 and 4 non-coaxial markers to define the segments respectively during four 30s trials at each speed. For the thoracic segment, markers were placed on the left and right acromions and the mid-sternum. For the pelvic segment, markers were placed on the right and left anterior and posterior superior iliac spines. The markers were considered to be rigid bodies because movements of the body segments between markers was minimal. Markers were also placed on the toes and heels of the subjects' shoes for recording and computing gait temporal distance factors (Fig. 1).

3.4 Measures

The main outcome measure was thorax CRP at two different walking speeds. The secondary variables were thoracic and pelvic range of motion (ROM). Secondary clinical outcomes were scores on the clinical evaluations (Functional Gait Assessment, BesTest, CM) and the correlation of the clinical and kinematic outcomes.

3.4.1 Continuous relative phase (CRP)

The CRP describes the instantaneous differences in both velocity and position between two body segments.[61] For every point in time, the inverse tangent of the ratio between gait and position was obtained for each segment and the phase angle of one segment was then subtracted from the other:

$$CRP_{th;pl} = \text{Phase angle\_th } (t) - \text{Phase angle\_pl } (t)$$

For the CRP measure, a value of 180° represents perfect anti-phase movement and a difference of 0° indicates prefect in-phase movement. The CRP between thoracic (th) and pelvic (pl) segments during walking were computed in each of the two planes (yaw, roll).

3.4.2 Thoracic and pelvic range of motion (ROM)

For each gait cycle, thoracic and pelvic angular rotation amplitudes were determined in two planes (yaw, roll). Rotations in the pitch plane were not considered since they are influenced by head position and gaze direction which were not rigidly controlled in this study.[62] Rotation amplitudes were defined as absolute angular differences in degrees from the maximal to minimal rotation within each cycle (heel off to heel off on the same leg). Outcomes were measured separately for the left gait cycle and right gait cycle for the control group and separately for the paretic and non-paretic gait cycle in the stroke group.

3.4.3 Arm swing range of motion

Total arm swing amplitude in the sagittal plane was recorded during each gait cycle. The amplitude was defined as the absolute distance in mm from the minimal to the maximal points of the arm swing recorded from the marker placed on the finger relative to the acromion marker, in the same arm for each gait cycle and averaged across cycles.

3.4.4 Clinical evaluations

For all control and stroke subjects, impairment and function related to gait and balance activities were measured with the BesTest[63] and the Functional Gait Assessment (FGA).[64] In addition to these two tests, for stroke subjects the

Chedoke- McMaster Stroke Assessment was also was used to measure impairment. Clinical evaluations were done by experienced physiotherapists who were blind to study goals.

A. Measurement of impairment

The BesTest is a clinical balance assessment tool that includes 36 items, grouped into 6 sections on scales ranging from 15 to 21 points where maximum points on each section indicate no impairment or disability. The scale enables clinicians to determine the type of balance problems experienced by the patient. Sections 1 to 5 of the BesTest assess impairment. Section 6 assesses gait stability, a measure of gait function. The BesTest has excellent inter-rater reliability (ICC 0.91) and it is valid for people with balance disorders.[63] Validity in patients with stroke has not been estimated.

Sections of the BesTest:

1) Biomechanical Constraints: evaluates the quality of standing balance using items such as the hip and ankle functional strength, the foot base of support, center of mass alignment and the ability to stand up from sitting on the floor. The inter-rater reliability of this section is ICC 0.80.[63]

2) Stability limits/ Verticality: evaluates the ability to move the center of mass over the base of support without losing balance or changing the base of support. The functional reach forward and lateral tasks were used in which the subject stood with his/her arms out in 90 degrees flexion or abduction (with respect to the forward or the lateral reach) and reached as far as he/she could without rotating

the trunk, lifting the heel or protracting the scapula. Another task in this section is leaning to the side and vertically from the sitting position (ICC 0.79). [63]

3) Anticipatory postural adjustments: evaluates the ability to actively move the body's center of mass by changing body positions in standing by tasks such as sit to stand, rise to toes, standing on one leg, touch alternate stairs and raise the arms fast with weights of 2.5 kg (ICC 0.92).[63]

4) Postural responses: evaluates compensatory stepping and in-place postural responses as a result of an external perturbation that is created by the examiner.

5) Sensory orientation: evaluates the changes in the amount of body sway when standing on different surfaces with eyes open and closed (visual). In this test, balance is assessed when somatosensory information from the support surface is changed and the proprioceptive system is challenged; ICC 0.96.[63]

6) Stability in gait: evaluates gait stability by challenging different systems while walking. The items include changing gait speed, making fast turns, narrowing the base of support and cognitive challenge (ICC 0.88). [63]

The Chedoke- McMaster Stroke Assessment (CM) assesses physical impairment and disabilities that may appear after stroke. It includes six dimensions: shoulder pain, postural control, arm, hand, leg and foot movement. Each dimension is scaled on a 7-point scale where a maximum score of 7 indicates no impairment or disability. All dimensions have an excellent inter-rater reliability (ICC 0.93-0.98).[55]

B. Measurement of function

Gait performance was measured using the FGA. The FGA is a 10-item assessment with each item scored on a 4 point scale (0 -3) where 3 indicates normal function. The FGA includes 7 of the 8 items of the Dynamic Gait Index (DGI), which evaluates different walking patterns or the performance of different tasks while walking. Three additional items assessing function in gait ("gait with narrow base of support", "ambulating back-wards" and "gait with eyes closed") differentiate between the DGI and the FGA. The DGI was found as a valid tool to assess dynamic balance in older adults [65] and recently, the DGI was found to be valid for people with stroke by comparing results of DGI with the Timed Up and Go (TUG), Berg Balance Scale, timed walking test (10 m walking test) and the Activities–specific Balance Confidence rating score (ABC; r=0.63-0.83).[66] The FGA was developed by Wrisley et al[64] when they found moderate reliability of the DGI for people with moderate dizziness and a potential ceiling effect for high functioning walkers. Also, they found that the instructions of some items in the DGI were too vague. For these reasons, the FGA was chosen to measure gait performance over the DGI despite its validity not being shown in the stroke and elderly populations.

3.5 Analysis

3.5.1 Gait temporal and distance factors - kinematic analysis:

For each subject, a sequence of at least 10 strides (gait cycle) was selected from each of the 4 trials. A stride is defined as 2 steps: from one heel contact to the next heel contact of the same foot. The selection of the 10 strides was based on observation of consistent amplitudes and frequencies of the time series of movements of the heel markers of both legs. Gait temporal distance factors identified were step length, step width for both legs, stride frequency (cadence) and gait speed. Step length was defined as the antero-posterior distance (y axis) and step width as the medio-lateral distance (x axis) between the left and right heel markers during double stance. Cadence (number of strides / sec) was computed by adding the number of both right and left steps during the gait trial divided by the time of the trial in seconds. Gait speed was computed based on the inverse of the treadmill speed. For each variable, the mean and SD value of the entire trial (the selected gait cycles) was computed.

3.5.2 Thorax and pelvis range of motion - kinematic analysis

From each group of markers (which was considered as a rigid body) placed on the thorax and pelvis, segment reference frames were defined and transformed by the Vicon system into a global coordinate system of x, y, z Euclidean coordinates. In this reference frame, rotation around the y- and z-axes corresponded to roll (coronal plane) and yaw (transverse plane) respectively. Each angle was measured from 0 to 360º where right rotation around the y-axis and left rotation around the z-axis were positive values. Rotation amplitudes were defined as absolute angular differences in degrees from the maximal to minimal rotation within each cycle (heel-off to heel-off on the same leg). Outcomes were measured separately for the left and right gait cycles for the control group and separately for the paretic and non-paretic gait cycles in the stroke group.

3.5.3 Arm swing – kinematic analysis

Range of motion of each arm was calculated from the y coordinate (sagittal) of the finger marker of all 3 projections. The range of motion was defined as the distance from the minimum swing point to the maximum point in space for each arm swing cycle in mm and then averaged across trials.

3.5.4 CRP - kinematic analysis

The CRP was calculated for every point in time during the trial, as the inverse tangent of the ratio between velocity and position that was obtained for each segment and the phase angle of one segment was then subtracted from the other: CRPth-pl = Phase angle_th(t) – Phase angle_pl(t). The mean CRP of all gait cycles in each trial was obtained and averaged across trials.

3.5.5 Statistical analysis

Independent t-tests were carried out to compare healthy and stroke groups' average scores of the outcomes. Homogeneity of variances was verified using Levene's test. In cases where assumption of homogeneity was violated non-parametric independent t-test (Mann-Whitney U-test) were used. To adjust for multiple comparisons within the same family of analysis, Bonferonni corrections were applied. Additionally to examine differences of two speeds conditions a paired-t-test was conducted separately for each group, the stroke and the healthy. Based on a-priory knowledge and peculiarity of the study sample distributions a one-tail Spearman's correlation was carried out to examine the relationship between the kinematic outcomes (CRP, pl ROM, th ROM) and clinical evaluations (FGA, BesTest, CM).

CHAPTER 4: RESEARCH MANUSCRIPT

Title

"Deficits in inter-segmental trunk coordination during walking are related to clinical balance and gait function in chronic stroke"

Revital R. Hacmon, BPT, Tal Krasovsky, M.Sc., Anouk Lamontagne, PT, PhD, Mindy F. Levin, PT, PhD

4.1 Abstract

Background and purpose: Inter-segmental trunk coordination is an important factor affecting gait speed. Decreased speed is one of many gait deficits in individuals with stroke, in addition to changes in temporal and distance gait factors, decreased endurance and balance problems. These other gait deficits may also be related to changes in coordination, specifically of trunk movements in the transverse plane (yaw). The aim of the present study was to determine the relationship between thoracic and pelvic inter-segmental coordination during gait and functional deficits related to gait and balance in individuals with chronic stroke.

Subjects: The study included 11 chronic stroke subjects and 11 age-matched healthy controls.

Procedure: Clinical and kinematic data were recorded in 2 sessions: (1) Clinical evaluations of trunk/limb impairment using the Chedoke-McMaster Stroke Assessment, functional gait using the Functional Gait Assessment and balance using the BesTest. (2) Gait kinematics were recorded during eight 30 s walking

trials on a self-paced treadmill at 2 different speeds (comfortable and matched between the groups). In addition, 3D angular ranges of movements of the thorax and the pelvis and trunk inter-segmental coordination (thorax-pelvis) using the continuous relative phase (CRP) was analyzed.

Results: Comfortable gait speed was slower in stroke (0.78 m/s) compared to healthy (1.22 m/s subjects but cadences were matched. At both comfortable and matched (0.97-0.98 m/s) speeds, stroke subjects used more thoracic range of motion and tended to have a more in-phase compared to anti-phase thorax-pelvis coordination pattern. CRP was more in-phase in the stroke group compared to the healthy subjects at the comfortable walking speed. At matched speed, there were no differences between groups in kinematic data but stroke subjects had higher cadence, wider and shorter steps. Clinically, thoracic ROM and CRP correlated with functional gait and balance measures (BEStest, FGA) only in the stroke group when walking at comfortable speed.

Conclusion: The use of higher cadence, wider and shorter steps at matched speed, with no differences in kinematic data between groups show that the stroke group used multiple modifications (compensations) in the gait pattern to maintain CRP at the faster gait speed.

While walking in comfortable gait speed, stroke patients walk slower and have deficits in inter-segmental trunk coordination in the transverse plane which may be related to deficits in functional gait performance. The lower performance on the BEStest (measure of postural control) and the FGA tests (measure of the ability to perform complex locomotor tasks: e.g. changing direction or speed, head turning while walking) may suggest that fine movement coordination is required to achieve desired task goals while maintaining balance and body progression. It is suggested that treatment focusing on improving the quality of inter-segmental trunk coordination while walking may improve postural control and the ability to perform complex locomotor tasks in stroke patients, together with improving gait speed.

Key words: stroke, gait, inter segmental coordination, thorax-pelvis coordination, continuous relative phase (CRP), clinical evaluations.

4.2 Introduction

Changes in temporal or distance factors related to walking are common following a stroke. While most individuals are independent functional walkers by one year post-stroke, [5] walking speed and endurance may not be sufficient for them to function effectively in the community.[6,7] For example, individuals with stroke at all stages (acute, sub-acute and chronic) who could walk independently for 10 m, could not maintain a comfortable walking speed and walked a smaller distance compared to healthy age-matched subjects.[6,9] Temporal factors of gait such as speed and cadence usually decrease with a concomitant increase in double support and stride time. Longer stance than swing phases have been found in the less-affected leg. The deficits related to distance factors can be decreased stride length, increased step width and toe-out angle and asymmetry in the step length. Some of the changes are significantly speed dependent (i.e. stride length, cadence).[12] Trunk control is an important predictor of functional locomotor recovery after stroke.[37] Most measures of trunk control have been based on the strength of the trunk musculature. For example, individuals with sub-acute and chronic stroke have lower levels of trunk muscle strength compared to age-matched control groups.[38-40] However, in a series of studies Verheyden and colleagues[41] developed the Trunk Control Test (TCT), in which trunk 'performance' was defined as trunk muscle strength as well as the ability to perform gross movements such as rolling, sitting up from lying and balancing in sitting. However, like most clinical scales, scores refer to the degree to which the task is accomplished rather than to how the task is performed. Information about the quality of movement is desirable so that clinicians can better understand the movement deficit and focus treatment interventions, which often include rehabilitation of movements of the trunk.[19]

Another measure of trunk performance, developed by the same group, is the Trunk Impairment Scale (TIS).[41] The TIS evaluates static and dynamic sitting balance and trunk coordination, where trunk coordination is defined as the ability to rotate the upper or lower parts of the trunk symmetrically to both the non-paretic and the paretic sides. Strong relationships between trunk performance and balance, gait and functional ability indicate that both scales (TCT and TIS) are good clinical assessment tools.[40] For the TIS, the items assessing trunk coordination have a specific timing requirement (e.g., to rotate the upper trunk 6 times, where each shoulder should be moved forward 3 times within 6 s). These items, however, focus on trunk coordination during sitting and not during gait. To the best of our knowledge, no clinical measure assesses trunk coordination during gait and only one study has investigated the relationship between trunk coordination and gait in individuals with stroke.

The quality of trunk movement is related to the coordination between the movements of different trunk segments during functional activities, specifically in the transverse (yaw) plane. Trunk coordination has been characterized by inter-segmental phase relationships (continuous relative phase, CRP) between movements of the thorax and pelvis during gait and is affected by gait speed.[45-47,53,57] In young healthy subjects, during treadmill walking, the range of motion of the pelvis in the transverse plane (yaw) increased with gait speeds up to 0.7-1.0 m/s and decreased from 1.1-1.3 m/s while the CRP only increased with speed. However, the relationship between the thoracic range of motion and gait speed remains unclear.[45,46] When healthy subjects walked at slow speeds, the two segments were close to in-phase but when the speed was increased beyond 0.83 m/s, the relationship changed in the direction of anti-phase indicating a bifurcation point in the stability of the coordination pattern.[45,46,67]
In the coronal plane (roll plane; side flexion movements) a similar speed effect on the CRP has been observed, while in the sagittal plane (pitch plane; flexion-extension), the effect was opposite- the faster the subjects walked, the more an in-phase pattern occurred in that plane.[48]

Inter segmental coordination during gait has also been characterized in adults with different musculoskeletal and neurological deficits. In patients with low back pain (LBP), range of motion (ROM) of the thoracic, lumbar and pelvic segments in the transverse plane did not differ from the healthy group despite differences in stride length. However, there were differences in the CRP values at the transverse plane:

at a comfortable gait speed (LBP 0.91 m/s, control 1.3 m/s) the CRP was lower (more in-phase) in the LBP group compared to the control group and remained lower at higher walking speeds (1.05-1.66 m/s). Gait in healthy subjects was characterized by the ability to change from one coordination (CRP) pattern to another (i.e., in-phase to anti-phase) with the change in the gait speed. However, patients with LBP tended to adopt a pattern of in-phase coordination between thorax and pelvis rotation across a wider range of walking speeds. An inability to change the coordination pattern according to speed may be a result of musculoskeletal spinal stiffness and deficits in gait stability.[49] Patients with Parkinson's disease (PD) were also reported to have lower inter-segmental thorax and pelvis CRP values for rotations in the transverse plane when walking at different gait speeds ranging from 0.2-1.4 m/s compared to a control group. However, the PD group was still able to increase CRP values with increases in gait speed.[52] Only one group has evaluated the effect of gait speed (ranges 0.25-1.5 m/s) on trunk coordination in stroke subjects in the transverse plane.[53] In both, chronic stroke and healthy subjects, CRP, thorax and total trunk ROM values were linearly related to gait speed: the faster the subjects walked, the higher the CRP (more anti-phase) and total trunk ROM values. However, the pelvic ROM increased when speed increased only in the control group. Overall, stroke subjects did not differ from healthy controls in mean values of CRP, pelvis ROM and total ROM. However, stroke subjects used a greater thoracic ROM compared to controls.

These studies suggest that abnormal trunk movement and coordination in the transverse plane during walking in patients with various pathologies may be related to gait deficits. Specifically, transverse thoracic and pelvic movements have been shown to be asymmetrical and to be more tightly coupled during locomotion. Gait deficits are common in chronic stroke patients in addition to deficits in trunk muscle activation and voluntary trunk movements. Thus, it is likely that gait performance in stroke patients may be related to deficits in the coordination of transverse thoracic and pelvic movement. We hypothesized that individuals with stroke would have deficits in inter-segmental coordination between thoracic and pelvic movements in the transverse plane during gait compared to healthy control subjects. We further hypothesized that individuals with stroke who have better inter-segmental trunk coordination would perform better on functional gait and balance measures. Preliminary results have been published in abstract form Hacmon et al.[68]

4.3 Methods

Subjects

Eleven stroke and 11 healthy control subjects participated (Table 1). Control subjects were age-matched to the stroke group. Inclusion criteria for the stroke subjects were (1) presence of a first unilateral ischemic stroke; (2) aged 40-75 yrs; (3) ability to walk independently without walking aides on a treadmill; (4) impairment in postural control, as indicated by score ≤6/7 on the Chedoke-McMaster (CM) Impairment Inventory;[55] (5) impairment in walking speed (≤ 0.95

ms^{-1}); and (6) some residual arm movement (Chedoke-McMaster Arm Scale ≥3/7). The exclusion criteria were (1) marked visuospatial neglect (Bells Test <26/35)[56] or visual field deficits (medical chart) and (2) significant deficits in upper or lower limb proprioception (<14/16 Fugl-Meyer Scale position sense.[69] An additional exclusion criterion for both groups was the presence of a previous orthopedic or rheumatic condition that may have interfered with walking ability. The study was approved by the Ethics Committee of CRIR (Centre for Interdisciplinary Research in Rehabilitation). All subjects signed a consent form prior to the participation.

Table 1: *Demographic data and results of clinical evaluations for control and stroke subjects*

Demographic data	Control (n=11)	Stroke (n=11)
Gender, n (%)		
Male	8 (72.7%)	8 (72.7%)
Female	3 (27.3%)	3 (27.3%)
Paretic side, n (%)		
Left	-	6 (54.5%)
Right	-	5 (45.5%)
Age (yrs), mean (SD)	68.0 ± 4.6	62.0 ± 11.1
Time since onset (months), mean (SD)	-	32.5 ± 25.5
Gait speed – comfortable (m/s)	1.22±0.21	0.78±0.2*
Gait speed – matched (m/s)	0.92±0.17	0.97±0.19
Functional Gait Assessment, mean (SD)	28.4 ± 1.8	23.3±3.5*
BesTest total score, mean (SD)	97.2 ± 7.0	87.6±9.8*
BesTest 1 (0-15)	12.5 ± 1.8	11.8 ±1.7
BesTest 2 (0-21)	19.3 ± 1.6	18.6 ±1.6
BesTest 3 (0-18)	16.6 ± 2.2	13.6 ±2.2*
BesTest 4 (0-18)	15.3 ± 2.2	13.7 ±3.3
BesTest 5 (0-15)	14.2 ± 1.7	13.0 ±1.7
BesTest 6 (0-21)	19.4 ± 1.2	16.7 ±3.1

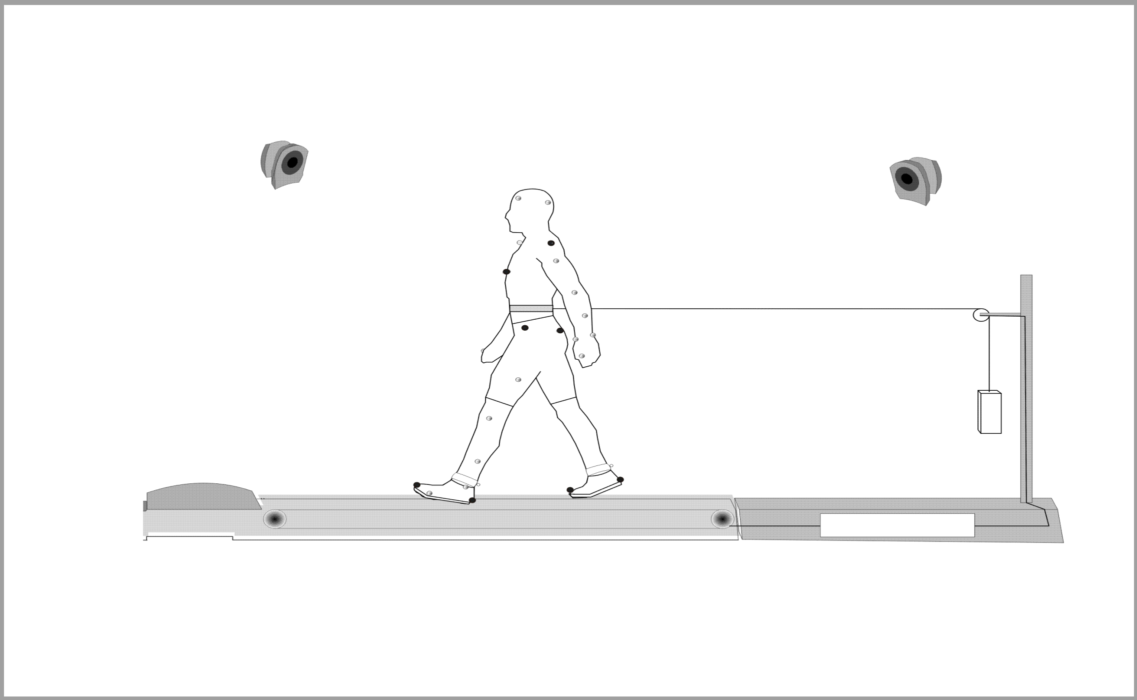
* =p<0.05

Experimental paradigm

All sessions took place in the Virtual Reality and Mobility Laboratory of the Jewish Rehabilitation Hospital (JRH) in Laval, Quebec. To prevent falling, subjects wore a safety harness that could move over the length and width of the treadmill and was attached to the ceiling. Subjects walked on a self-paced motorized treadmill (Fig. 1). Treadmill speed was determined by the length of a cord attached to the harness 1.88 m behind the subject. Treadmill speed changed in relation to the cadence of the subject. Safety switches were mounted on the treadmill and the control box that stopped the treadmill if necessary.

Subjects walked at their comfortable speed and at matched speeds (as fast as they could without running for stroke subjects or 20% slower than their comfortable speed for Controls), since CRP is related to gait speed. To minimize variability in walking speed, subjects followed the pacing of a metronome that was matched to their walking cadence at each speed. After becoming familiar with walking on the treadmill, four baseline 30 s trials were used to calculate the mean comfortable walking speed which was then used to compute faster/slower walking speed conditions in each group. Participants were instructed to walk naturally in the middle of the belt. In addition, subjects wore a heart-rate monitor to ensure that heart rate did not exceed 70% of maximum (220-age) in each trial.

Fig.1: *Experimental set-up*



Kinematic data were collected using a 12 camera high-resolution (~1 mm) Vicon-512™ system with reflective markers and a sampling rate of 120 Hz for 4 30s trials at each speed. Thoracic and pelvic rotations in 3 dimensions (pitch, roll and yaw) were recorded using the segment 3 and 4 non-coaxial markers respectively. For the thoracic segment, markers were placed on the left and right acromions and the mid-sternum. For the pelvic segment, markers were placed on the right and left anterior and posterior superior iliac spines. Markers were also placed on toes and heels of the subject's shoes for recording and computing gait temporal and distance factors as well as on the tip of the third finger of each hand for parameters of arm swinging.

Clinical evaluation

For all control and stroke subjects, impairment and function related to locomotor activities were measured with the BesTest [63] and the Functional Gait Assessment (FGA).[64] In addition to these 2 tests, the CM was also used to measure impairment in stroke subjects. Clinical evaluations were done by experienced physiotherapists who were blind to study goals.

Measurement of impairment: The BesTest is a clinical balance assessment tool that includes 36 items, grouped into 6 sections. These items are evaluated by sub-scales, the maximum scores of which range from 15 to 21 points, where maximum points on each section indicate no impairment or disability. Sections 1 to 5 assess impairment. Section 6 assesses gait stability, a measure of activity. The BesTest has excellent inter-rater reliability (ICC 0.91) and it is valid for people with balance disorders.[63] Validity in patients with stroke has not been estimated.

The Chedoke-McMaster Impairment Inventory assesses physical impairment and disabilities that may occur after stroke. It includes six dimensions (shoulder pain, postural control, arm, hand, leg, foot) that are scaled on 7-point scales where a maximum score of 7 indicates no impairment or disability. All dimensions have an excellent inter-rater reliability (ICC 0.93-0.98).[55]

Measurement of function: Gait performance was measured using the FGA. The FGA is a 10-item assessment with each item scored on a 4 point scale (0 -3) where 3 is normal function. The FGA includes 7 out of 8 items from the Dynamic Gait Index (DGI) and 3 additional items assessing gait function ("gait with narrow base of support", "ambulating backwards", "gait with eyes closed"). Concurrent validity was shown for people with stroke by comparing results of DGI with the Berg Balance Scale, the 10 m timed walking test, the Timed Up and Go (TUG) and the Activities–Specific Balance Confidence rating score (ABC; r=0.63-0.83).[66] The FGA was chosen over the DGI due to its superior standardization of instructions and the lower probability of a ceiling effect for high functioning walkers due to the 3 additional items.

Kinematic evaluation

Gait distance and temporal factors, trunk segment kinematics and arm swing distance for each subject were analyzed from a sequence of at least 10 strides (gait cycles) selected from each of the 4 trials. Selection was based on the observation of consistent amplitudes and frequencies of the time series of movements of the heel markers of both legs. Factors identified were step length, step width, stride frequency (cadence) and gait speed. Step length was defined as the antero-posterior distance (y axis) and step width as the medio-lateral distance (x axis) between the left and right heel markers during double-support in stance. For each variable, the mean and SD value of the entire trial was computed. Stride frequency/cadence was calculated as the number of strides/s and was computed by adding the number of right and left steps. Gait speed was computed based on the inverse of the treadmill speed.

For each gait cycle, thoracic and pelvic angular rotation amplitudes were determined in two planes (roll and yaw). Rotations in the pitch plane were not considered since they are influenced by head position and gaze direction which were not rigidly controlled in this study.[62] Rotation amplitudes were defined as absolute angular differences in degrees from the maximal to minimal rotation within each cycle (heel-off to heel-off on the same leg). Outcomes were measured separately for the left and right gait cycles for the control group and separately for the paretic and non-paretic gait cycles in the stroke group. From each group of segment markers placed on the thorax and pelvis, segment reference frames were defined and transformed into a global coordinate system of x, y, z Euclidean coordinates. In this reference frame, rotation around the y- and z-axes corresponded to roll (coronal plane) and yaw (transverse plane) respectively. Each angle was measured from 0 to 360º where right rotation around the y- axis and left rotation around the z-axis were positive values.

The length of the arm swing was computed in each cycle for each arm as the distance in mm from the maximal backward to maximal forward displacement of the arm from the finger marker.

The primary outcome measure was the continuous relative phase (CRP) of the thoracic (th) and pelvic (pl) trunk segments during walking for each of the two planes (roll, yaw). CRP describes the instantaneous differences in both position and velocity between two body segments.[61] For every point in time, the inverse tangent of the ratio between gait and position was obtained for each segment and the phase angle of one segment was then subtracted from the other:

$$CRP_{th;pl} = \text{Phase angle\_th } (t) - \text{Phase angle\_pl } (t)$$

where a phase difference of 180° represents perfect anti-phase movement and a difference of 0° indicates prefect in-phase movement. The mean (SD) CRP of all gait cycles in each trial was obtained and averaged across trials.

Statistical analysis:

Data are presented as mean values ± standard deviation, and as r values for the correlation data. Independent t-tests were used for between-group comparisons. Paired t-tests were carried out when the comparisons were within group. Significance levels were adjusted for multiple comparisons using Bonferroni corrections. When homogeneity of variances differed, non-parametric statistics were substituted (Mann-Whitney U-test). Correlations were evaluated with Spearman's one-tailed tests.

4.4 Results

All subjects walked on the treadmill at two different speeds. Stroke subjects walked approximately 36% slower than the control subjects at the comfortable speed (control: 1.22±0.21 m/s; stroke: 0.78±0.2 m/s, $p<0.001$). When asked to walk faster, speed of walking in stroke subjects was still 20% slower than controls' comfortable speed (Table 1). One stroke subject could not walk faster than her comfortable speed.

At comfortable speed, both groups had a similar cadence. However, step width and step length differed between groups: stroke subjects made wider (~15%) and shorter (~25%) steps with both legs (Table 2). This was significant ($p<0.01$-0.02) for all comparisons except for step width for the left/paretic leg following Bonferroni corrections. Within the stroke group, the step length but not the step width on the paretic side was greater than the non-paretic side (paired t-test, $p<0.01$).

At matched speed, stroke subjects had a higher cadence ($p<0.001$) compared to control subjects. With respect to the other gait temporal distance factors, only step length on the non-paretic leg was shorter in the stroke group compared to the right leg in the control group ($U=13.5$, $p<0.003$).

Table 2: *Kinematic outcomes of both groups when walking at two speeds (mean ± SD).*

Outcomes	Comfortable speed		Matched speed	
	Control	Stroke	Control	Stroke
CRP-yaw (deg)	109.4 ± 45.4	65.02 ± 43.03*	77.0 ± 42.6	75.1 ± 53.4
Thorax ROM – yaw (deg)	10.5 ± 3.3	13.3 ± 5.4	11.0 ±3.1	12.2 ± 3.9
Pelvis ROM – yaw (deg)	8.5 ± 2.8	9.1 ± 3.8	10.0 ± 3.9	7.9 ± 2.8
Total cadence (steps/min)	106.4 ± 12.1	102.6 ± 9.8	84.8 ± 9.2	111.5 ± 10.0*
Step width left/paretic gait cycle (cm)	9.4 ± 3.0	12.3 ± 3.5	10.4 ± 2.9	11.8 ± 3.1
Step width right/non-paretic gait cycle(cm)	8.9 ± 2.2	12.8 ± 3.0*	9.6 ± 2.2	12.4 ± 3.0*
Step length left/paretic cycle (meters)	0.58 ± 0.09	0.46 ± 0.11*	0.56 ± 0.06	0.49 ± 0.11
Step length right/non-paretic cycle (meters)	0.57 ± 0.12	0.42 ± 0.09*	0.56 ± 0.05	0.44 ± 0.08*
Arm sagittal movement paretic arm/non- dominant arm (mm)	453.5 ± 90.1	292.9 ± 151.3*	410.7± 102.7	285.5± 135.4*
Arm sagittal movement non-paretic arm/ dominant arm (mm)	526.8 ± 205.6	492.0 ± 141.0	408.4± 136.7	483.5± 172.4

* =p< 0.05; CRP-continuous relative phase; ROM-range of motion;

Comparison of trunk kinematics between groups walking at matched speed.

Examples of thorax and pelvis ROM in a single trial in one control (A) and one stroke (B) subject are shown in Fig. 2. In the example shown, the pelvis and thorax ROM in the control subject were similar to each other but in the stroke subject, thoracic ROM was greater than that of the pelvis.

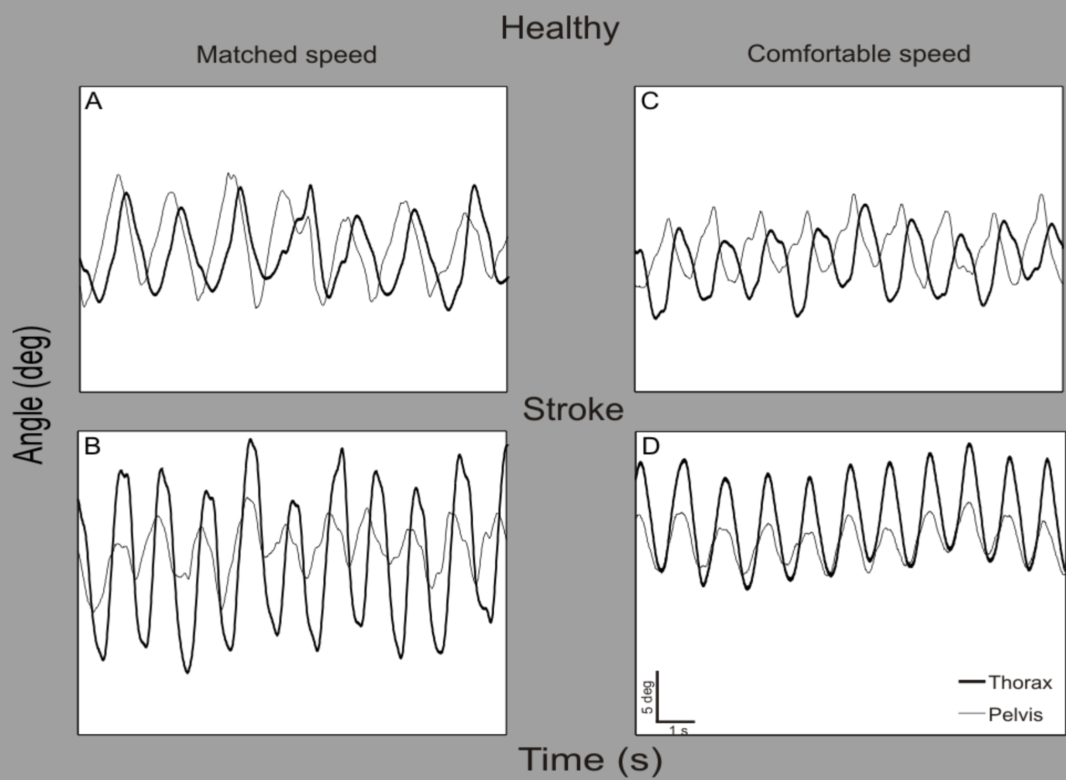


Fig. 2 *Examples of thorax and the pelvis movement of one stroke and one control subject, during gait trials at both speeds.*

Within the same group, in the yaw plane differences between thorax and pelvis ROM were only present in the stroke group (Fig.3): ROM thorax: 12.2°±3.9°; range 6.7° to 13.9°; pelvis: 7.9°±2.7°; range 4.9° to 18.5°; paired t =-5.021, p<0.001. No differences were found in the roll plane.

The yaw inter-segmental coordination at this speed is illustrated in the left panel of Fig 4. There was no difference in CRP between groups. In the control group, eight subjects had CRP yaw values between 0º to 90º with three of them being strongly in-phase (24.4°, 31.1°, 39.6°). The other three subjects had CRP yaw values between 90º and 180º with one being strongly anti-phase (157.3°). For the stroke group, the distribution was similar (7 subjects = 0º to 90º; 3 subjects = 90º to 180º), but all 3 of the subjects in the second group had strongly anti-phase CRPs. For roll, the CRP was closer to anti-phase in both groups (not shown in Fig. 4). Four control and 3 stroke subjects had values between 0º and 90º. Of these, 2 controls and 1 stroke subject had strongly in-phase CRP values. Seven subjects in both groups had CRP values between 90º and 180º. Of these, the CRP was strongly anti-phase in 5 controls and 3 stroke subjects.

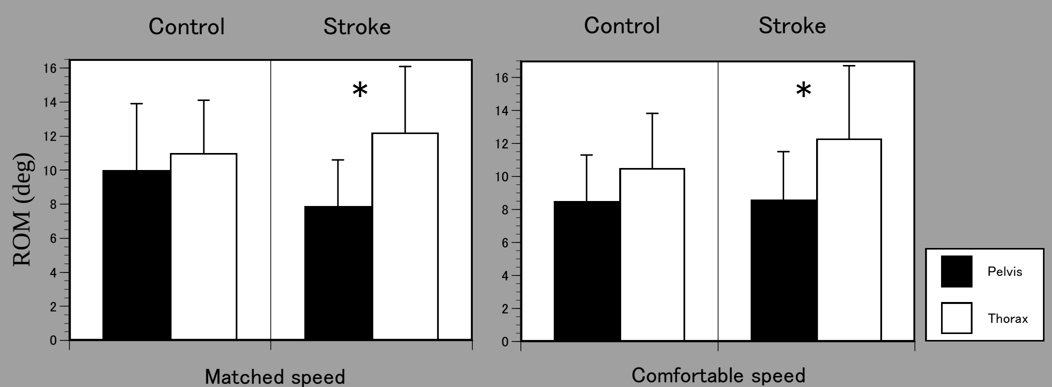


Fig 3. *Differences between pelvis and thorax range of motion (ROM) for each group when walking at matched and at comfortable speeds. * = p<0.05*

Examples of single walking trials in a representative subject in each group are shown in Fig. 2C, D. Similar to the effect at matched speed, stroke subjects used more thoracic than pelvic rotation in the yaw plane (ROM thorax: 13.3°±5.4°; range 7.6° to 23.5°; pelvis: 9.1°±3.3°; range 4.6° to 14.7°; paired t= -4.287, p<0.002, Fig. 3). Unlike the pattern in the matched speed condition, however, healthy subjects used more pelvic than thoracic rotation in roll (paired t=2.519, p<0.03).

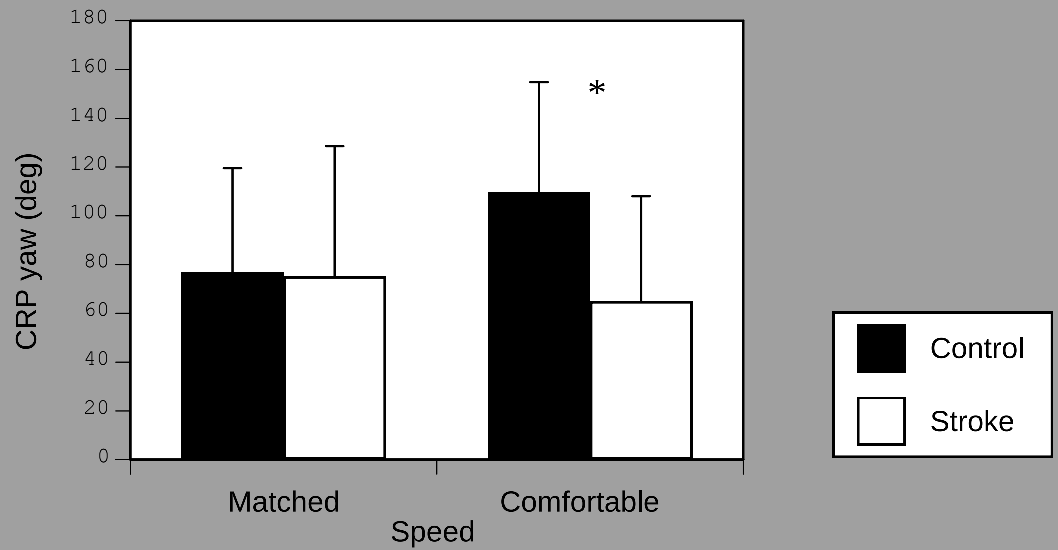


Fig. 4 *Continuous relative phase (CRP) between thorax and pelvis movements in the yaw plane in each group for each walking speed. * = p<0.05*

Comparison of trunk kinematics between groups walking at matched speed. The CRP in the yaw plane was significantly more anti-phase in the control group compared to the stroke group (p<0.03; Fig. 4 right panel). In the roll plane, there was a similar tendency, but the difference was not significant. In the yaw plane, 5 controls had CRP values between 0º and 90º, of which 1 was strongly in-phase and 6 had values between 90º and 180º, with 5 of them being strongly anti-phase. For the stroke group, 7 subjects had values between 0º and 90º with 2 of them strongly in-phase and 4 had values between 90º and 180º, with 2 of them strongly anti-phase.

In the control group the arm swing amplitude of the non-dominant arm was 86% of that of the dominant arm, whereas in the stroke group, the ratio was 60% for the paretic arm compared to the non-paretic arm. The difference in the amplitude of the arm swing was significant only in the stroke group ($p<0.01$; Table 2).

Correlations between kinematic data and clinical scores.

Since clinical evaluations were performed at the subject's comfortable speed, only the correlations between kinematic data recorded at this speed and scores on clinical tests were evaluated in both groups. In the control group, there were markedly fewer correlations compared to the stroke group (Table 3) and all of them occurred for measures in the yaw plane. In the control group, the CRP was moderately inversely correlated with the 'Biomechanical Constraints' section on the BesTest (BesTest1). Pelvic ROM was negatively correlated with the FGA. Finally, the thoracic ROM was inversely correlated with BesTest5 which measures 'Sensory Orientation'. In the stroke group, kinematic data were moderately correlated only with CM subscales at the impairment level of the ICF. Thus, thoracic ROM was inversely correlated with 3 CM subscales (arm, leg, foot: $r = -0.71$ to -0.78) and pelvic ROM was inversely correlated with CM arm and foot scores ($r = -0.67$ to -0.70). However, the coordination measure (CRP) correlated with most of the clinical measures at the activity level, but not the impairment level (BesTest 1, 3, 4 ,6: $r = 0.52$ to 0.68; FGA: $r = 0.63$). The same sub-scales of the BesTest ($r = -0.58$ to -0.83) and FGA ($r = -0.54$) were also correlated with thoracic ROM in the yaw plane. Pelvic ROM in the yaw plane was negatively correlated with the 'Anticipatory Postural Adjustment" section of the BesTest (BesTest 3: $r = - 0.56$) and the FGA ($r = -0.54$).

Table 3: *Correlations between kinematic outcomes and clinical scores*

	Stroke				Controls			
	CRP yaw	ROM yaw pl	ROM yaw th	CRP roll	CRP yaw	ROM yaw pl	ROM yaw th	CRP roll
BesTest 1	0.608*	-	-0.642*	-	0.552*	-	-	-
BesTest 2	-	-	-	-	-	-	-	-
BesTest 3	0.681*	-0.561*	-0.828**	-	-	-	-	-
BesTest 4	0.527*	-	-0.577*	-	-	-	-	-
BesTest 5	-	-	-	-	-	-	-0.711**	-
BesTest 6	0.590*	-	-0.627*	-	-	-	-	-
BesTest total	0.755**	-	-0.627*	-	-	-	-	-
FGA	0.630*	-0.539*	-0.539*	-	-	-0.607*	-	-
CM postural control	-	-	-	-	-	-	-	-
CM arm	-	-0.640*	-0.775**	-0.539*	-	-	-	-
CM hand	-	-	-	-	-	-	-	-
CM leg	-	-	-0.710**	-	-	-	-	-
CM foot	-	-0.666*	-0.728**	-	-	-	-	-

FGA - Functional Gait Assessment; CM = Chedoke-McMaster Scale; th = thorax; pl = pelvis

* = $p<0.05$, one tailed Spearman's correlation
** = $p<0.01$, one tailed Spearman's correlation

4.5 Discussion

The comfortable walking speed in stroke subjects was slower than healthy controls but the cadence was similar between groups. Despite the matched cadences, steps were shorter and wider and the thorax-pelvis coordination in yaw, measured by the CRP, was more in-phase in the stroke group. In addition stroke subjects used relatively more thoracic compared to pelvic rotation during walking. In a previous study, differences in gait parameters were reported when both gait speed and cadence were matched between groups[14]. Thus, it is likely that stroke subjects were able to adapt spatial gait parameters (step width, length) in order to maintain cadence. CRP differences at faster and slower gait speeds were consistent with those previously reported.[53]

Results at matched speed show that CRPs were similar between groups but that stroke subjects used different temporal and spatial gait parameters. Thus, altered temporal and spatial gait parameters may be compensatory mechanisms that were used in our group of subjects to maintain cadence at comfortable speed walking and CRP at the faster walking speed.

Kinematic measures were correlated with clinical function at comfortable speed in both groups. Unlike healthy subjects, CRP and thoracic ROM in stroke subjects correlated with many gait and balance clinical scores.

All stroke subjects were high functioning, could walk independently and participate in community activities. They had a mean gait speed of 0.78 m/s which was close to the functional gait speed described for this age group (0.8 m/s).[10] However, stroke subjects still performed significantly less well than the age-matched healthy subjects on clinical gait and balance tests.

Clinical correlations showed that at comfortable gait speed, the more anti-phase the pattern of trunk inter-segmental coordination (higher the CRP), the better balance and gait functional performance. Furthermore, trunk kinematics were also correlated with performance on the more challenging locomotor tasks on the FGA scale. The comparison of trunk kinematics with functional gait performance at comfortable speed may be more clinically feasible than comparisons at matched speeds when the system is forced to walk at an unnatural pace. Our findings suggest that deficits in trunk inter-segmental correlation may limit functional gait performance.

The relationship between gait speed and functional performance has been well-documented.[10,70-72] For example, the ability to walk faster is correlated with the ability to accomplish more walking-related functional activities[70] . Fewer studies have identified the underlying movement deficits or biophysical mechanisms related to deficits in gait speed. Daly et al.[73] found that hip and knee inter-joint coordination was disrupted in stroke and that the amount of disruption was strongly correlated with gait speed: the lower the coordination, the slower the gait speed. In terms of thorax-pelvis coordination in the transverse plane (CRP), Wagenaar & Beek[53] found that the faster the gait speed, the more the pattern was in anti-phase in both healthy and stroke subjects. Lamontagne et al. (2005) also examined trunk-pelvis coordination in stroke, with and without head turns using other measures of coordination and reported that faster walking was associated with better anti-phase coordination. In our study, a relationship between CRP and gait speed was found in healthy but not stroke subjects. Indeed, in stroke subjects, increasing gait speed did not increase anti-phase inter-segmental patterning (Fig. 3C) and there also was no correlation between gait speed and CRP or ROM values. However, stroke subjects did not walk at faster speeds equivalent to those of the healthy group and we did not investigate the limits of the range of CRP values possible in subjects with stroke. This suggests a link between gait speed, thorax-pelvis inter-segmental coordination and functional gait performance. Thus, improving inter-segmental coordination may lead to better gait- and balance-related functional outcomes in patients with stroke.

Increase in relative thoracic ROM in stroke may be a compensatory mechanism

With respect to ROM, we found negative correlations between both thorax and pelvis ROM and clinical functional evaluation: the FGA and the BesTest. We also found that the severity of the impairment, evaluated by the CM scale, was highly inversely correlated with thoracic ROM and moderately inversely correlated with pelvic ROM. This suggests that the greater the range of thoracic and pelvic movements, the greater the impairment and the lower the clinical performance.

The increased range of thoracic movement observed in our study may be related to a compensatory mechanism previously described in patients with stroke. Stroke patients use compensatory movements of the trunk to assist the production of arm reaching and pointing and grasping from the sitting position.[74-76] In standing, movement of the thoracic portion of the trunk was associated with assisting arm rhythmical bilateral arm swinging in patients with stroke. For example, Ustinova et al[77] characterized the relationship between movements of the upper trunk (thorax) and arm swinging in healthy and stroke subjects. During in-phase arm swinging, there was a negative relationship between displacement of the thorax and the arm such that anterior arm swinging was inversely correlated with posterior displacement of the ipsilateral shoulder. However, this correlation was positive in stroke subjects indicating that they used the trunk to assist arm swinging in standing. The abnormal anterior thoracic movement also resulted in a forward shift of the center of mass of the body. Thus, it is likely that patients with stroke in our study may have used a similar mechanism (greater thoracic rotation) to compensate for the deficit in the arm swing amplitude of the paretic arm and to facilitate anterior shifting of the center of mass in order to assist forward gait progression.

4.6 Clinical Significance

Achieving better gait performance is one of the goals of stroke rehabilitation. In the clinic there are many different approaches to improve gait performance. Techniques such as muscle strengthening, functional electrical stimulation, partial body-weight support, biofeedback, treadmill training, task-specific gait training and Proprioceptive Neuromuscular Facilitation (PNF) are commonly used, yet there is no clinical evidence supporting the choice of one technique over the other.[20,54] Most approaches aim at decreasing tone and the influence of abnormal synergies as well as facilitating normal movements in functional patterns. The theoretical basis is derived from general concepts of biomechanics, skill acquisition and learning, human ecology and physiology such that normal movement is thought to occur on a background of normal tonus and equilibrium reactions.[78] Different physiotherapy textbooks[19,79-82] discuss the importance of trunk movements and trunk muscle strengthening, but there are few examples or explanations that take into account the coordination between movements of different trunk segments. One exception is the PNF technique which is used to facilitate and instruct patients to perform contra-lateral (anti-phase) movements between the thorax and the pelvis in different positions, including gait,[83] but the physiological or motor control basis of this approach has not hitherto been described.

Movements of the trunk and the coordination between the thorax and the pelvis segments during gait have been well-described in healthy populations. Our study shows that these relationships are disrupted in stroke and that this disruption is related to deficits in functional gait. Our results suggest that improvements in thorax-pelvis coordination in patients with stroke may reduce the use of thoracic movement compensations and lead to better functional gait and balance performance.

4.7 Limitations of the study and generalizability

Several limitations of this study should be acknowledged. First of all, the use of a treadmill may impair the generalizability of the results to over-ground walking. We used a self-paced treadmill which responds to the individual's gait speed instead of driving it, to minimize this difference. Another limitation of the study is the use of metronome pacing to assist subjects in maintaining the same gait speed across trials. Future studies may be done without metronome pacing and with over-ground walking. Finally, the selection criteria for the stroke group which required them to be high-functioning limits the generalizability of the results to stroke patients with lower levels of function.

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Chapter 5: CONCLUSIONS AND FUTURE DIRECTIONS

5.1 Conclusions

Difficulty in walking is a common deficit post stroke that is usually defined as hemiparetic gait. Hemiparetic gait may have one or more of the following characteristics: slow speed, asymmetry in step length and width, difficulty with weight bearing on the paretic limb and disrupted coordination between different joints or muscles groups.

From a typical patient's point view, regaining the ability to walk independently is one of the most important goals of the rehabilitation program.[84] Therapists and researchers place much focus on the rehabilitation of gait, and through the years different techniques and approaches to assess and treat walking have been developed.

There is no clear evidence that suggests choosing one technique over the other to ensure the best walking rehabilitation program. Most physiotherapists use several techniques and approaches to optimize the treatment. Their choice follows clinical experience, available evidence and the results of the clinical evaluations of the patients.

It is interesting to note that most clinical evaluations provide clinicians with an idea about the patient’s ability to accomplish the task but few focus on characterizing how the task is performed or the quality of the performance.

However, in order to help clinicians choose between different treatment approaches, a better understanding of the normal and the abnormal biomechanical (kinematic) movement patterns during gait is necessary. Since clinicians usually do not have access to instrumented kinematic data analysis, better clinical assessment scales are needed in order to characterize the relationship between kinematic deficits and commonly used clinical evaluation scales. This project examined the kinematics of trunk (thorax-pelvis) inter-segmental coordination during walking and its relationship with clinical evaluations in individuals post stroke. Our results showed that stroke subjects have deficits in trunk inter-segmental coordination when walking at a comfortable gait speed compared to healthy controls walking at their comfortable gait speed. It is important to note that the comfortable gait speed of the stroke subjects was slower than the comfortable gait speed in healthy subjects. We found that the coordination pattern of the stroke group was more in in-phase compared to the healthy controls, which may be related to their slower gait speed as suggested in previous studies, and that the stroke subjects used relatively more thorax than pelvis rotation. We also found correlations between the inter-segmental coordination scores and clinical evaluations: the higher the score of the coordination measure, the better the performance on the clinical scores. Correlations were also found between the thoracic ROM and the clinical scores: the higher the thoracic ROM the lower the clinical evaluation performance.

In conclusion, subjects with a higher level of function and lower impairment had better trunk inter-segmental coordination and less movement in thoracic rotation- which is similar to the behavior of the healthy controls in our study. Our results suggest that improvements in thorax-pelvis coordination in patients with stroke may reduce the use of thoracic movement compensations and lead to better functional gait and balance outcomes.

5.2 Future directions

Future studies may be done with some changes and additional conditions such as:

(1) Over-ground walking – to test gait ability in a more realistic condition in order to maximize the similarity between the laboratory experiment and real life. In addition, walking on different surfaces can be also studied.

(2) Stroke patients with lower levels of function – our study had high functioning stroke subjects that did not represent all walking characteristics in the whole stroke population.

(3) Comparison with the coordination of other segments (head, arms, legs) – walking is a complex task which involves multiple body segments. Movements or coordination amongst the other segments may also be affected by stroke. Arms and legs are directly connected to the thorax and pelvis, and therefore may have a direct impact on the trunk coordination. The head may affect the coordination by when control of gaze is required.

(4) Analyzing the relationship between transverse trunk coordination and the coordination of the trunk in the other planes – the movements within the different planes may affect each other and any changes in the relationships between the planes as a result of disability after stroke can affect gait.

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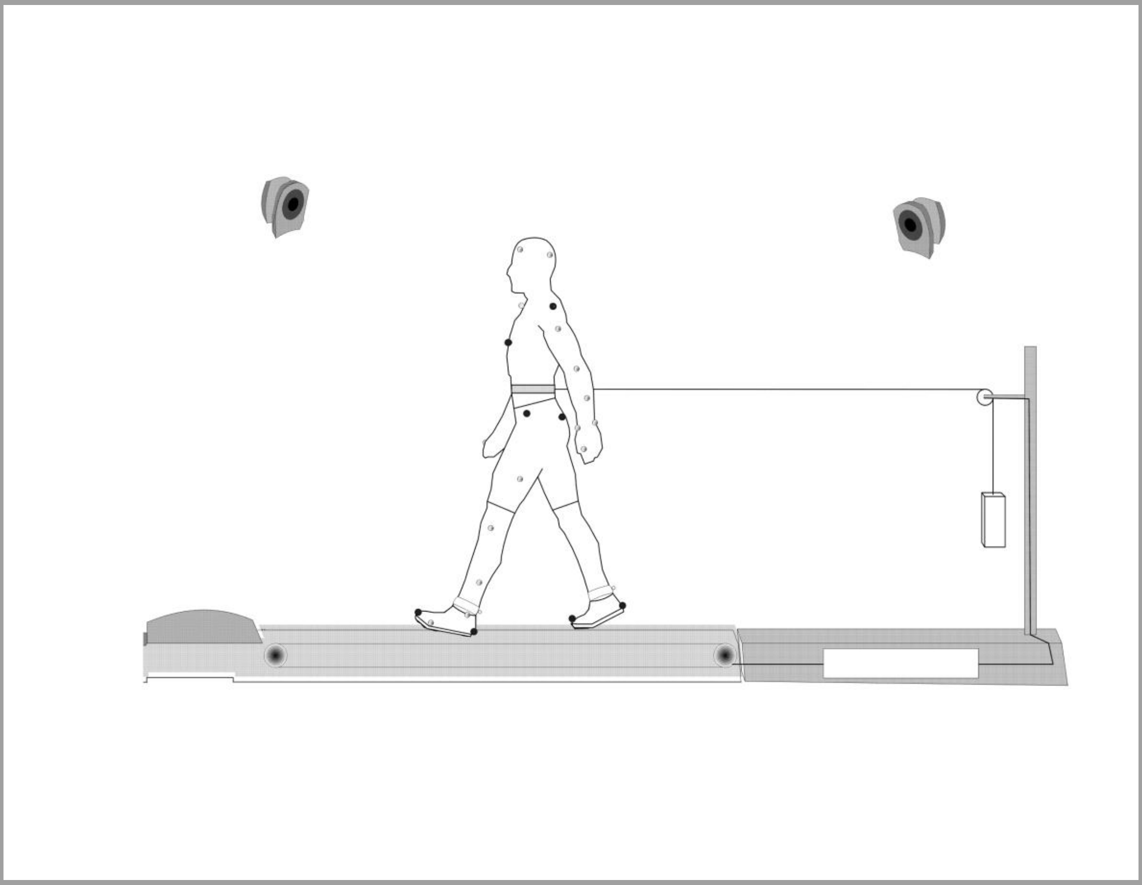
Appendix I: Experimental Set-up



Appendix II: FGA

Jewish Rehabilitation Hospital – Physiotherapy department

Functional Gait Assessment work sheet

Name of patient:_________________

Date:___________________________

	Description of items	Time	Score
1	**Gait level surface 20' (6 m)** (3) normal, no aid, < 5.5 sec, deviation not greater 6" (15.24 cm) w.w. (2) able w/aid, mild deviation, < 6 sec, deviates 6-10" (15.24-25.4 cm) w.w. (1) able, abnormal gait, imbalance, > 7 sec, deviates + 12" (30.48) w.w. (0) unable, needs assistance, deviation <+15" (38.1 cm) , imbalance		
2	**Change in gait speed** (fast at 5' (1.5 m), slow at 10' (3 m)) (3) significant difference in walking speed, deviation < 6" (15.24 cm) w.w. (2) mild dev (6-10"/15.24-25.4 cmof w.w.) **or** no significant diff in speed, uses aids (1) moderate deviation (10-15" out w.w.), minor change speed, loses balances + continues (0) no change in speed, loses balance, needs support, dev > 15" (38.1 cm) w.w.		
3	**Gait + horizontal head turns** (look right X 3 steps, look left X 3 steps – repeat x2) (3) smooth head turns + normal gait, deviation < 6" (15.24 cm) w.w. (2) smooth turns, small gait chng, deviation 6-10", (15.24-25.4 cm) w.w. ,uses aids (1) slows down, dev 10-15" w.w., staggers but can continue (0) severe disruption gait, stops, staggers, reaches, needs support, dev < 15" (38.1 cm) w.w.		
4	**Gait + vertical head turns** (look up X 3 steps, down X 3 steps, straight-repeat x2) (3) smooth head turns + normal gait, dev < 6" (15.24 cm)w.w. (2) smooth turns, small gait change, deviation 6-10" (15.24-25.4 cm) w.w. uses aids (1) slows down, staggers, can continue, deviation 10-15" w.w. (0) severe disruption gait, stops, staggers, reaches, needs support, dev >15" (38.1 cm) w.w.		
5	**Gait and pivot turn** (quick turn and stop) (3) pivot < 3 s + stops quickly, no imbalance (2) pivot > 3 s + stops, no imbalance or pivots, < 3 sec few steps imbalance (1) slow turn, cuing, several small steps (0) not safe, assistance needed		
6	**Step <u>over</u> obstacle** 2 shoe boxes taped together (9", 22.86 cm) or 1 shoe box (4,5", 11.43 cm) (3) steps over 2 boxes without change in speed + gait (2) steps over 1 box without change in speed + gait (1) steps over 1 box, slows down, adjusts steps, verbal cuing (0) assistance needed		
7	**Gait with narrow base** (arms folded, 10 heel-toe steps) (3) completes 10 steps without staggering (2) completes 7 – 9 steps (1) completes 4 – 7 steps (0) walks less than 4 steps or needs assistance		
8	**Gait with eyes closed** (walk between two marks (20 ft apart) eyes closed) (3) normal gait, < 7 sec, dev 6" (15.24 cm) w.w. (2) uses aid, < 9 sec, dev 6 -10" (15.24-25.4 cm) vw.w., mild gait deviation (1) slow abnormal gait, > 9 sec, dev 10 – 15" (25.4-38.1 cm) (0) needs assistance, dev < 15" (38.1 cm), will not attempt		
9	**Ambulate backwards** (walk until told to stop) (3) walks normal gait, deviation <6" (15.24 cm) (2) mild impairment, uses aids, slower gait, deviation < 10" (25.4 cm) (1) moderate impairment, slow abnormal gait, imbalance, deviation < 15" (38.1 cm) (0) needs assistance, severe gait deviation, dev >15" (38.1 cm)		
10	**Stairs** (up, turn, down, as would at home) (3) alternating feet, no rail (2) alternating feet rail (1) two feet to a stair, rail (0) not safe		

Appendix III: BesTest

Balance Evaluation Systems Test (BESTest)

eAppendix.
Continued

Balance Evaluation Systems Test (BESTest) Interrater Reliability

Subjects should be tested with flat-heeled shoes or shoes and socks off. If subject must use an assistive device for an item, score that item one category lower. If subject requires physical assistance to perform an item, score the lowest category (0) for that item.

I. Biomechanical Constraints

Section I: ______/15 Points

1. Base of support

(3) Normal: Both feet have normal base of support with no deformities or pain
(2) One foot has deformities and/or pain
(1) Both feet have deformities *OR* pain
(0) Both feet have deformities *AND* pain

2. CoM alignment

(3) Normal AP and ML CoM alignment and normal segmental postural alignment
(2) Abnormal AP *OR* ML CoM alignment *OR* abnormal segmental postural alignment
(1) Abnormal AP *OR* ML CoM alignment *AND* abnormal segmental postural alignment
(0) Abnormal AP *AND* ML CoM alignment

3. Ankle strength and range

(3) Normal: Able to stand on toes with maximal height and to stand on heels with front of feet up
(2) Impairment in either foot of either ankle flexors or extensors (ie, less than maximum height)
(1) Impairment in two ankle groups (eg, bilateral flexors or both ankle flexors and extensors in one foot)
(0) Both flexors and extensors in both left and right ankles impaired (ie, less than maximum height)

4. Hip/trunk lateral strength

(3) Normal: Abducts both hips to lift the foot off the floor for 10 s while keeping trunk vertical
(2) Mild: Abducts both hips to lift the foot off the floor for 10 s but without keeping trunk vertical
(1) Moderate: Abducts only one hip off the floor for 10 s with vertical trunk
(0) Severe: Cannot abduct either hip to lift a foot off the floor for 10 s with trunk vertical or without trunk vertical

5. Sit on floor and stand up *Time ______ seconds*

(3) Normal: Independently sits on the floor and stands up
(2) Mild: Uses a chair to sit on floor *OR* to stand up
(1) Moderate: Uses a chair to sit on floor *AND* to stand up
(0) Severe: Cannot sit on floor or stand up, even with a chair, or refuses

II. Stability Limits/Verticality

Section II: ______/21 Points

6. Sitting verticality and lateral lean

Lean			Verticality		
Left	Right		Left	Right	
(3)	(3)	Maximum lean, subject moves upper shoulders beyond body midline, very stable	(3)	(3)	Realigns to vertical with very small or no overshoot
(2)	(2)	Moderate lean, subject's upper shoulder approaches body midline or some instability	(2)	(2)	Significantly overshoots or undershoots but eventually realigns to vertical
(1)	(1)	Very little lean, or significant instability	(1)	(1)	Failure to realign to vertical
(0)	(0)	No lean or falls (exceeds limits)	(0)	(0)	Falls with the eyes closed

(Continued)

7. Functional reach forward *Distance reached: ______ cm OR ______ inches*

(3) Maximum to limits: >32 cm (12.5 in)
(2) Moderate: 16.5-32 cm (6.5-12.5 in)
(1) Poor: <16.5 cm (6.5 in)
(0) No measurable lean—or must be caught

8. Functional reach lateral *Distance reached:* ***Left*** ____ cm (____ in) ***Right*** ____ *cm (____ in)*

Left	Right	
(3)	(3)	Maximum to limit: >25.5 cm (10 in)
(2)	(2)	Moderate: 10-25.5 cm (4-10 in)
(1)	(1)	Poor: <10 cm (4 in)
(0)	(0)	No measurable lean, or must be caught

III. Anticipatory Postural Adjustments — Section III: _____/18 Points

9. Sit to stand

(3) Normal: Comes to stand without the use of hands and stabilizes independently
(2) Comes to stand on the first attempt with the use of hands
(1) Comes to stand after several attempts or requires minimal assist to stand or stabilize or requires touch of back of leg or chair
(0) Requires moderate or maximal assist to stand

10. Rise to toes

(3) Normal: Stable for 3 s with good height
(2) Heels up, but not full range (smaller than when holding hands so no balance requirement) *OR* slight instability and holds for 3 s
(1) Holds for less than 3 s
(0) Unable

11. Stand on one leg

Left *Time in seconds ______*	Right *Time in seconds ______*
(3) Normal: Stable for >20 s	(3) Normal: Stable for >20 s
(2) Trunk motion, *OR* 10-20 s	(2) Trunk motion, *OR* 10-20 s
(1) Stands 2-10 s	(1) Stands 2-10 s
(0) Unable	(0) Unable

12. Alternate stair touching *# of successful steps: ______ Time in seconds: ______*

(3) Normal: Stands independently and safely and completes 8 steps in <10 s
(2) Completes 8 steps in <10 seconds, but shows instability such as inconsistent foot placement, excessive trunk motion, hesitation, or arhythmical stepping
(1) Completes <8 steps—without assistance (ie, assistive device) *OR* >10 s for 8 steps
(0) Completes <8 steps in 10 s, even with assistive device

13. Standing arm raise

(3) Normal: Remains stable
(2) Visible sway
(1) Steps to regain equilibrium/unable to move quickly without losing balance
(0) Unable, or needs assistance for stability

(Continued)

IV. Postural Responses

Section IV: ______/18 Points

14. In-place response—forward

(3) Recovers stability with ankles, no added arm or hip motion
(2) Recovers stability with arm or hip motion
(1) Takes a step to recover stability
(0) Would fall if not caught *OR* requires assist *OR* will not attempt

15. In-place response—backward

(3) Recovers stability at ankles, no added arm/hip motion
(2) Recovers stability with some arm or hip motion
(1) Takes a step to recover stability
(0) Would fall if not caught *OR* requires assistance *OR* will not attempt

16. Compensatory stepping correction—forward

(3) Recovers independently with a single, large step (second realignment step is allowed)
(2) More than one step used to recover equilibrium, but recovers stability independently *OR* one step with imbalance
(1) Takes multiple steps to recover equilibrium, or needs minimum assistance to prevent a fall
(0) No step *OR* would fall if not caught *OR* falls spontaneously

17. Compensatory stepping correction—backward

(3) Recovers independently with a single, large step
(2) More than one step used, but stable and recovers independently *OR* one step with imbalance
(1) Takes several steps to recover equilibrium or needs minimum assistance
(0) No step *OR* would fall if not caught *OR* falls spontaneously

18. Compensatory stepping correction—lateral

Left	Right
(3) Recovers independently with one step of normal length/width (crossover or lateral OK)	(3) Recovers independently with one step of normal length/width (crossover or lateral OK)
(2) Several steps used, but recovers independently	(2) Several steps used, but recovers independently
(1) Steps, but needs to be assisted to prevent a fall	(1) Steps, but needs to be assisted to prevent a fall
(0) Falls, or cannot step	(0) Falls, or cannot step

V. Sensory Orientation

Section V: ______/15 Points

19. Sensory integration for balance (modified CTSIB)

A–Eyes open, firm surface	B–Eyes closed, firm surface	C–Eyes open, foam surface	D–Eyes closed, foam surface
Trial 1 _____ s	Trial 1 _____ s	Trial 1 _____ s	Trial 1 _____ s
Trial 2 _____ s	Trial 2 _____ s	Trial 2 _____ s	Trial 2 _____ s
(3) 30 s stable	(3) 30 s stable	(3) 30 s stable	(3) 30 s stable
(2) 30 s unstable	(2) 30 s unstable	(2) 30 s unstable	(2) 30 s unstable
(1) <30 s	(1) <30 s	(1) <30 s	(1) <30 s
(0) Unable	(0) Unable	(0) Unable	(0) Unable

20. Incline–eyes closed

Toes Up

(3) Stands independently, steady without excessive sway, holds 30 s, and aligns with gravity
(2) Stands independently 30 s with greater sway than in item 19B *OR* aligns with surface
(1) Requires touch assist *OR* stands without assist for 10-20 s
(0) Unable to stand >10 s *OR* will not attempt independent stance

(Continued)

VI. Stability in Gait

Section V: _____/21 points

21. Gait–level surface

Time _______ seconds

(3) Normal: Walks 20 ft, good speed (≤5.5 s), no evidence of imbalance
(2) Mild: Walks 20 ft, slower speed (>5.5 s), no evidence of imbalance
(1) Moderate: Walks 20 ft, evidence of imbalance (wide base, lateral trunk motion, inconsistent step path)—at any preferred speed
(0) Severe: Cannot walk 20 ft without assistance or severe gait deviations *OR* severe imbalance

22. Change in gait speed

(3) Normal: Significantly changes walking speed without imbalance
(2) Mild: Unable to change walking speed without imbalance
(1) Moderate: Changes walking speed but with signs of imbalance
(0) Severe: Unable to achieve significant change in speed *AND* signs of imbalance

23. Walk with head turns—horizontal

(3) Normal: Performs head turns with no change in gait speed and good balance
(2) Mild: Performs head turns smoothly with reduction in gait speed
(1) Moderate: Performs head turns with imbalance
(0) Severe: Performs head turns with reduced speed *AND* imbalance *AND/OR* will not move head within available range while walking

24. Walk with pivot turns

(3) Normal: Turns with feet close, fast (≤3 steps) with good balance
(2) Mild: Turns with feet close, slow (≥4 steps) with good balance
(1) Moderate: Turns with feet close at any speed with mild signs of imbalance
(0) Severe: Cannot turn with feet close at any speed and significant imbalance

25. Step over obstacles

Time _______ seconds

(3) Normal: able to step over 2 stacked shoe boxes without changing speed and with good balance
(2) Mild: steps over 2 stacked shoe boxes but slows down, with good balance
(1) Moderate: steps over shoe boxes with imbalance or touches box.
(0) Severe: cannot step over shoe boxes *AND* slows down with imbalance or cannot perform with assistance.

26. Timed "Get Up & Go" Test

Get Up & Go: Time _______ seconds

(3) Normal: Fast (<11 s) with good balance
(2) Mild: Slow (>11 s) with good balance
(1) Moderate: Fast (<11 s) with imbalance
(0) Severe: Slow (>11 s) *AND* imbalance

27. Timed "Get Up & Go" Test With Dual Task

Dual Task: Time _______ seconds

(3) Normal: No noticeable change between sitting and standing in the rate or accuracy of backward counting and no change in gait speed
(2) Mild: Noticeable slowing, hesitation, or errors in counting backwards *OR* slow walking (10%) in dual task
(1) Moderate: Affects on *BOTH* the cognitive task *AND* slow walking (>10%) in dual task
(0) Severe: Cannot count backward while walking or stops walking while talking

(Continued)

Appendix IV CM

Chedoke-McMaster Stroke Assessment
SCORE FORM Page 1 of 4
IMPAIRMENT INVENTORY: SHOULDER PAIN AND POSTURAL CONTROL

POSTURAL CONTROL: Start at Stage 4. Starting position is indicated beside the item or underlined. No support is permitted. Place an X in the box of each task that is accomplished. Score the highest Stage in which the client achieves at least two Xs.

	SHOULDER PAIN				POSTURAL CONTROL
1	☐ constant, severe arm and shoulder pain with pain pathology in more than just the shoulder	1		☐	not yet Stage 2
2	☐ intermittent, severe arm and shoulder pain with pain pathology in more than just the shoulder	2	Supine	☐	facilitated log roll to side lying
			Side lying	☐	resistance to trunk rotation
			Sit	☐	static righting with facilitation
3	☐ constant shoulder pain with pain pathology in just the shoulder	3	Supine	☐	log roll to side lying
			Sit	☐	move forward and backward
			Stand	☐	remain upright for 5 sec
4	☐ intermittent shoulder pain with pain pathology in just the shoulder	4	Supine	☐	segmental rolling to side lying
			Sit	☐	righting within the base of support
			Sit	☐	standing up
5	☐ shoulder pain is noted during testing, but the functional activities that the client normally performs are not affected by the pain	5	Sit	☐	dynamic righting side to side, feet on floor
			Sit	☐	standup with equal weight bearing
			Stand	☐	step forward onto weak leg, transfer weight
6	☐ no shoulder pain, but at least one prognostic indicator is present • Arm Stage 1 or 2 • Scapula malaligned • Loss of range of shoulder movt - flexion/abduction < 90° or external rotation < 60°	6	Sit	☐	dynamic righting backward or sideways with displacement, feet off floor
			Stand	☐	on weak leg, 5 seconds ☐ sec
			Stand	☐	sideways braiding for 2 m
7	☐ shoulder pain and prognostic indicators are absent	7	Stand	☐	on weak leg: abduction of strong leg
			Stand	☐	tandem walking 2 m in 5 sec
			Stand	☐	walk on toes 2 m

☐ **STAGE OF SHOULDER PAIN**

☐ **STAGE OF POSTURAL CONTROL**

Chedoke-McMaster Stroke Assessment
SCORE FORM Page 3 of 4
IMPAIRMENT INVENTORY: STAGE OF RECOVERY OF LEG AND FOOT

LEG: Start at Stage 4 with the client in lying on back with knees bent and feet flat. FOOT: Start at Stage 3 with the client in supine. Test position is beside the item or underlined. If not indicated, the position has not changed. Place an X in the box of each task accomplished. Score the highest stage in which the client achieves at least two Xs. For "standing" test items, light support may be provided but weight bearing through the hand is not allowed. Shoes and socks off.

LEG

1	☐	not yet Stage 2
2 Crook lying	☐	resistance to passive hip or knee flexion
	☐	facilitated hip flexion
	☐	facilitated extension
3	☐	abduction: adduction to neutral
	☐	hip flexion to 90°
	☐	full extension
4	☐	hip flexion to 90° then extension synergy
	☐	bridging hips with equal weightbearing
Sit	☐	knee flexion beyond 100°
5 Crook lying	☐	extension synergy, then flexion synergy
Sit	☐	raise thigh off bed
Stand	☐	hip extension with knee flexion
6 Sit	☐	lift foot off floor 5X in 5 sec
	☐	full range internal rotation
	☐	trace a pattern: forward, side, back, return
7 Stand	☐	unsupported: rapid high stepping 10X in 5 sec
	☐	unsupported: trace a pattern quickly: forward, side, back; reverse pattern
	☐	on weak keg with support: hop on weak leg
	☐	**STAGE OF LEG**

FOOT

1	☐	not yet Stage 2
2 Crook lying	☐	resistance to passive dorsiflexion
	☐	facilitated dorsiflexion or toe extension
	☐	facilitated plantarflexion
3 Supine	☐	plantarflexion > ½ range
Sit	☐	some dorsiflexion
	☐	extension of toes
4	☐	some eversion
	☐	full inversion
	☐	legs crossed: dorsiflexion, then plantarflexion
5	☐	legs crossed: toe extension with ankle plantarflexior
	☐	sitting with knee extended: ankle plantarflexion, the dorsiflexion
Stand	☐	heel on floor: eversion
6	☐	heel on floor: tap foot 5X in 5 sec
	☐	foot off floor: foot circumduction
	☐	knee straight, heel off floor: eversion
7	☐	heel touching forward, then toe touching behind, repeat 5X in 10 sec
	☐	foot off floor: circumduction quickly, reverse
	☐	up on toes then back on heels 5X
	☐	**STAGE OF FOOT**

Chedoke-McMaster Stroke Assessment
SCORE FORM Page 2 of 4
IMPAIRMENT INVENTORY: STAGE OF RECOVERY OF ARM AND HAND

ARM and HAND: Start at Stage 3. Starting position: sitting with forearms in lap or supported on a pillow in a neutral position, wrist at 0° and fingers slightly flexed. Changes from this position are indicated by underlining. Place an X in the box of each tas accomplished. Score the highest Stage in which the client achieves at least two Xs.

ARM

1 ☐ not yet Stage 2

2 ☐ resistance to passive shoulder abduction or elbow extension
☐ facilitated elbow extension
☐ facilitated elbow flexion

3 ☐ touch opposite knee
☐ touch chin
☐ shoulder shrugging > ½ range

4 ☐ extension synergy, then flexion synergy
☐ shoulder flexion to 90°
☐ <u>elbow at side, 90° flexion:</u> supination, then pronation

5 ☐ flexion synergy, then extension synergy
☐ shoulder abduction to 90° with pronation
☐ <u>shoulder flexion to 90°</u>: pronation then supination

6 ☐ hand from knee to forehead 5X in 5 sec
☐ <u>shoulder flexion to 90°</u>: trace a vertical figure 8
☐ <u>arm resting at side of body</u>: raise arm overhead with full supination

7 ☐ clap hands overhead, then behind back 3X in 5 sec
☐ <u>shoulder flexion to 90°</u>: scissor in front 3X in 5 sec
☐ <u>elbow at side, 90° flexion:</u> resisted shoulder external rotation

☐ **STAGE OF ARM**

HAND

1 ☐ not yet Stage 2

2 ☐ positive Hoffman
☐ resistance to passive wrist or finger extension
☐ facilitated finger flexion

3 ☐ wrist extension > ½ range
☐ finger or wrist flexion > ½ range
☐ <u>supination, thumb in extension</u>: thumb to index finger

4 ☐ finger extension then flexion
☐ thumb extension > ½ range, then lateral prehension
☐ finger flexion with lateral prehension

5 ☐ finger flexion, then extension
☐ <u>pronation</u>: finger abduction
☐ <u>hand unsupported</u>: opposition of thumb to little finger

6 ☐ <u>pronation</u>: tap index finger 10X in 5 sec
☐ <u>pistol grip</u>: pull trigger, then return
☐ <u>pronation</u>: wrist and finger extension with finger abduction

7 ☐ thumb to finger tips, then reverse 3X in 12 sec
☐ bounce a ball 4 times in succession, then catch
☐ pour 250 ml. from 1 litre pitcher, then reverse

☐ **STAGE OF HAND**

Appendix V: Consent Form and ethics certificate

INFORMED CONSENT FORM

Project Leader

Anouk Lamontagne, PhD, PT
School of Physical and Occupational Therapy, McGill University and Jewish Rehabilitation Hospital (JRH)

Collaborators

Anatol G. Feldman, PhD
Department of Physiology, University of Montreal and CRIR - JRH

Mindy F. Levin, PhD, PT
School of Physical and Occupational Therapy, McGill University and CRIR - JRH

Melanie C. Baniña, MSc
PhD candidate, School of Physical and Occupational Therapy, McGill University

Tal Krasovsky, MSc
PhD candidate, School of Physical and Occupational Therapy, McGill University

Revital Hacmon, BSc
MSc candidate, School of Physical and Occupational Therapy, McGill University

Background

1. We are asking you to participate in a research project looking at walking stability and coordination of arm and leg movements. Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

   This consent form explains the aim of this study, the procedures, advantages, risks and inconvenience as well as the persons to contact, if necessary.

   This consent form may contain words that you do not understand. We invite you to ask any question that you deem useful to the researcher and the other members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

2. Individuals who have had a stroke often have difficulty walking, even after having completed their rehabilitation program. In particular, they may

encounter difficulties in coordinating the movements of the arms and legs while they walk. This project will assess the influence of arm swing on gait and the stability of walking under different conditions. We will examine if using arm swing in rehabilitation programs has the potential to further improve the walking ability of persons who have had a stroke.

Objectives

To examine the influence of arm swinging and the sudden stopping of the arm swinging or the leg movement (perturbation) on lower limb movements and muscle activation during walking in persons who have had a stroke, and to assess if this influence differs from that seen in persons who have not had a stroke.

Nature of my participation

This study will take place at the Virtual Reality and Mobility Research Laboratory of the Jewish Rehabilitation Hospital. I shall be attending three (3) evaluation sessions that will take approximately six (6) hours of my time. The first session will take one (1) hour, and the second and third sessions will take two and a half (2.5) hours each (including preparation time (1 hour) and evaluation time (1.5 hours)). In the first session, I will be asked questions about my confidence level when I walk, and about my handedness. I will also be asked to complete a short evaluation of my walking and of the function of my arms and legs.

Preparation

In order to record the movements of my body and limbs as I walk, small reflective markers will be taped onto my arms, forearms, wrists, thighs, legs and feet. In order to record the activity of my muscles as I walk, electrodes (small metal discs) will be taped to my arms, legs and back, and attached by wires to a small box that I will wear on a belt around my waist. I will not feel anything from these electrodes. It may be necessary to clean and shave the skin under the electrodes to ensure adhesion. The application of the electrodes and the markers means I will need to bring shorts and a short-sleeved top to wear during the study.

Evaluation

I will be asked to walk on a treadmill for 40 trials, for approximately 30 seconds at a time. After each walking trial I will be able to rest if I need to. My pulse will be monitored throughout the sessions to verify that I am comfortable. At all times I will be wearing a safety harness to prevent falls, and a researcher will be standing next to the treadmill for additional safety. The treadmill is fitted with several ‘Emergency Stop’ buttons that can be used if needed, and will immediately stop the treadmill movement.

Speed: At the start of the experiment (sessions 2 and 3), I will be given time to get used to the treadmill. During the session I will be asked to walk at two speeds: a comfortable pace and a faster pace. These speeds will be recorded and used in subsequent trials.

Leg/arm arrest: During the walking trials in sessions 2 and 3, one of my legs (session 2) or arms (session 3) will be attached to a mechanical device which will permit free movement of my arms and legs. However, in some of the trials, the device will briefly stop the movement of my leg or my arm. I will be asked to continue to walk despite these disturbances. I will not be asked to do these trials unless I am confident that I can do so safely. I will always be informed of the speed of walking and leg/arm arrest conditions before the trial starts.

Experimental setup

Risks and disadvantages

Risks associated with my participation in this study are minimal. During the walking evaluation I will be wearing a safety harness and a therapist will always be present to provide any assistance and to prevent falls. I may, however, feel tired following the evaluation. There is a possibility that a few small areas of skin (~ 2x2 cm each) may have to be shaved and cleaned with alcohol before positioning the electrodes. Although it is hypo-allergenic, the adhesive tape used to fix the electrodes and markers on my skin may occasionally produce some slight skin irritation. If this happens, a calming lotion is available and will be applied to the skin. The electrodes, razors and adhesive tape are all single-use and are new for each experiment.

Benefits

I will not personally benefit from participating in this study. However, the results from this study will provide information that will help in developing better techniques for the rehabilitation of persons who have had a stroke.

Financial compensation

Transportation and parking costs incurred through my participation in this project will be reimbursed up to a maximum of $30 per session, upon presentation of receipts.

Access to my medical chart

I authorize access to my medical file to the persons responsible for this project. I understand that only the relevant information concerning my medical history will be used by members of this research team.

Confidentiality

Any personal information making it possible to identify me will be kept confidential and will be filed by Dr. Mindy Levin in a locked cabinet at the Jewish Rehabilitation Hospital Motor Control Laboratory. The data relating to my evaluations will be transferred onto a computer file server where access is protected by passwords. Only members of the research team will have access to the information collected during the project. Otherwise, the information will be preserved for a maximum duration of 5 years following the end of the study, after which time it will be destroyed. The results of this research study will only be revealed in the form of scientific presentations or publications, without my name or identity exposed.

Questions concerning the study

The researchers present during the evaluation session should answer any questions I may have concerning the project in a satisfactory manner.

Withdrawal of subject from study

My participation in the research project described above is completely free and voluntary. I understand that I have the right to withdraw from the study at any moment without giving reason. This will not affect the health care and services I receive. Should I withdraw from the study, all documents and research data concerning myself will be destroyed.

Responsibility

By accepting to participate in this study, I do not surrender any of my rights and I do not liberate the researchers, their sponsors or the institutions involved from their legal and professional obligations.

Contact persons

If I need to ask questions about the project, signal an adverse effect and/or an incident, I can contact Tal Krasovsky or Melanie Baniña at (450) 688-9550 ext. 4824 or by email: tal.krasovsky@mail.mcgill.ca, melanie.banina@mail.mcgill.ca, or Mindy Levin, PhD, PT, at (514) 398-3894 or by email: mindy.levin@mcgill.ca.

If I have any questions regarding my rights and recourse concerning my participation in this study, I can contact Ms. Anik Nolet, Research Ethics Co-ordinator of the CRIR establishments at (514) 527-4527 ext. 2643, or by e-mail at: anolet.crir@ssss.gouv.qc.ca.

CONSENT

I declare to have read and understood the project, the nature and the extent of the project, as well as the risks and inconveniences I am exposed to as described in the present document. I have had the opportunity to ask all my questions concerning the different aspects of the study and to receive explanations to my satisfaction.

I, undersigned, voluntarily accept to participate in this study. I can withdraw at any time without any prejudice. I certify that I have received enough time to take my decision and I know that a copy of this consent form will be added to my medical file.

A signed copy of this information and consent form will be provided to me for my record.

Subject: ________________________________ **Date:** ____________________
(Signature)

________________________________ **Tel:** ______________________
(Print name)

COMMITMENT OF RESEARCHER

I, undersigned, ______________________________ **, certify**

(a) having explained to the signatory the terms of the present form;
(b) having answered all questions he/she asked concerning the study;
(c) having clearly told him/her that he/she is at any moment free to withdraw from the research project described above; and
(d) that I will give him/her a signed and dated copy of the present document.

Signature: ________________________________ **Date:** ______________________

Comité d'éthique de la recherche
des établissements du CRIR

Montréal, le 24 septembre 2009

Anouk Lamontagne, Ph.D.
CRIR-Hôpital juif de réadaptation
3205, place Alton-Goldbloom
Laval (Québec) H7V 1R2

Centre de réadaptation Lucie-Bruneau

Centre de réadaptation Constance-Lethbridge

Hôpital juif de réadaptation

Institut Nazareth et Louis-Braille

Institut Raymond-Dewar

Institut de réadaptation de Montréal

Partenaires

Centre de réadaptation Estrie

Centre de réadaptation La Ressourse

Centre de réadaptation en déficience physique Le Bouclier

N/réf : CRIR-330-1007

Madame Lamontagne,

Nous avons bien reçu votre formulaire « R » dûment rempli concernant votre projet :

"Arm and Leg Coordination during Gait".

Nous avons donc procédé au renouvellement de votre certificat d'éthique dont nous vous joignons la copie. Ce certificat est valable pour un an.

Par ailleurs, le CÉR demande à être informé de toutes modifications qui pourraient être apportées au projet de recherche mentionné ci-dessus (Formulaire M).

Recevez, Madame Lamontagne, l'expression de nos meilleures salutations.

Anik Nolet

Me Anik Nolet
Coordonnatrice à l'éthique de la recherche
des établissements du CRIR

AN/cl

PJ: Certificat d'éthique

Comité désigné en vertu de l'article 21 du Code civil du Québec

2275, avenue Laurier Est
Montréal (Québec) H2H 2N8 Canada
T (514) 527-4527 (2643)
F (514) 521-4058 www.crir.ca

Comité d'éthique de la recherche des établissements du CRIR

CRIR

Certificat d'éthique

(Renouvellement)

Pour fins de renouvellement, le Comité d'éthique de la recherche des établissements du CRIR, selon la procédure d'évaluation accélérée en vigueur, a examiné le projet de recherche CRIR-**330-1007** intitulé :

« Arm and Leg Coordination during Gait ».

Présenté par: **Anouk Lamontagne, Mindy F. Levin, Anatol G. Feldman**

Le présent projet répond aux exigences éthiques de notre CÉR. Ce projet se déroule dans les sites du CRIR suivants : **Hôpital juif de réadaptation, Institut de réadaptation Gingras-Lindsay de Montréal.**

Ce certificat est valable pour un an. En acceptant le présent certificat d'éthique, le chercheur s'engage à :

1. Informer, dès que possible, le CÉR de tout changement qui pourrait être apporté à la présente recherche ou aux documents qui en découlent (Formulaire M) ;
2. Notifier, dès que possible, le CÉR de tout incident ou accident lié à la procédure du projet ;
3. Notifier, dès que possible, le CÉR de tout nouveau renseignement susceptible d'affecter l'intégrité ou l'éthicité du projet de recherche, ou encore, d'influer sur la décision d'un sujet de recherche quant à sa participation au projet ;
4. Notifier, dès que possible, le CÉR de toute suspension ou annulation d'autorisation relative au projet qu'aura formulée un organisme de subvention ou de réglementation ;
5. Notifier, dès que possible, le CÉR de tout problème constaté par un tiers au cours d'une activité de surveillance ou de vérification, interne ou externe, qui est susceptible de remettre en question l'intégrité ou l'éthicité du projet ainsi que la décision du CÉR ;
6. Notifier, dès que possible, le CÉR de l'interruption prématurée, temporaire ou définitive du projet. Cette modification doit être accompagnée d'un rapport faisant état des motifs à la base de cette interruption et des répercussions sur celles-ci sur les sujets de recherche ;
7. Fournir annuellement au CÉR un rapport d'étape l'informant de l'avancement des travaux de recherche (formulaire R) ;
8. Demander le renouvellement annuel de son certificat d'éthique ;
9. Tenir et conserver, selon la procédure prévue dans la *Politique portant sur la conservation d'une liste des sujets de recherche*, incluse dans le cadre réglementaire des établissements du CRIR, une liste des personnes qui ont accepté de prendre part à la présente étude ;
10. Envoyer au CÉR une copie de son rapport de fin de projet / publication.

Me Michel T. Giroux
Président du CÉR

Date d'émission
18 septembre 2009

Appendix VI: Plug-in-Gait Marker Placement