NEW INSIGHT INTO POSTURAL ADJUSTMENTS DURING LOCOMOTION POST STROKE

Dahlia Kairy

School of Physical and Occupational Therapy

McGill University, Montreal

January 2002

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements of the degree of

Masters of Science (Rehabilitation Sciences)

0-612-78906-3

TABLE OF CONTENTS

PREFACE

Structure of thesis

This is a manuscript-based thesis. Chapter 1 contains the rationale and objectives, followed by a literature review of (1) postural control in healthy individuals and stroke patients, and (2) outcome measures of balance and mobility. Chapter 2 presents the first manuscript, "A postural adaptation test for stroke patients", submitted for publication to *Clinical Rehabilitation*. The second manuscript, entitled "Kinematic strategies in response to head movements executed while walking in normal and hemiparetic subjects" submitted to *Gait and Posture* is found in Chapter 3. Finally, in Chapter 4, a summary of the results from the two studies is presented and future directions are discussed.

Contribution of authors

For both studies, I was the primary person responsible for conception and design of the studies, subject recruitment, data collection and analysis, and writing of the manuscripts. For both studies, Dr. Nicole Paquet and Dr. Joyce Fung, thesis co-supervisors, contributed intellectually to the conception and design of the studies, and participated actively in analysis and interpretation of the data, as well as revision of the manuscripts.

Acknowledgments

I would like to take this opportunity to thank many people who have truly made this a memorable journey. First, I am very thankful to have chosen such a wonderful team to work with. I am extremely grateful to my supervisors, Dr. Joyce Fung and Dr. Nicole Paquet for sharing their extensive knowledge and expertise with me. They always provided me with continued guidance and immense inspiration.

A special thanks to my fellow graduate students at the Jewish Rehabilitation Hospital Research Centre for making it such a fantastic work environment. I am especially grateful to Dr. Anouk Lamontagne for her guidance. The success of this project would not have been possible without the theoretical and technical expertise of the researchers and assistants in the lab. As well, I would like to thank Dr. Francine Malouin for her insightful feedback on my research proposal.

I am grateful for the financial support provided by the following agencies: Fonds de la recherche en santé du Québec (FRSQ), Réseau provincial de recherche en adaptation-réadaptation (REPAR), Jewish Rehabilitation Hospital Foundation, Ordre professionnel des physiothérapeutes du Québec (OPPQ), Natural Sciences and Engineering Research Council of Canada (NSERC), and Faculty of Graduate Studies and Research of McGill University. I also extend my sincere gratitude to all the subjects who kindly participated in the studies.

Finally, to my wonderful family for their continued support. In particular, to my husband, Paul, for encouraging me to pursue this degree and always believing in me, and to my parents and brother, Raphael, for always keeping me focused and striving for the best.

Abstract

A new clinical measure of postural adaptation, the Advanced Mobility and Balance Scale (AMBS), was developed to assess balance capacities of stroke patients in standing and walking. In the first pilot study, involving 12 stroke patients and 6 healthy subjects, we found excellent *interrater reliability* and reasonable *discriminative capacity* of the AMBS. However, high-level functioning stroke subjects could not be differentiated from healthy subjects.

In order to refine the scoring of the AMBS for better discrimination, we conducted a kinematic analysis of head turning while walking in 10 stroke patients and 5 age-matched healthy subjects. Results showed that stroke patients manifested disrupted *head-trunk-pelvis coordination* and increased *footpath deviation* during head turns towards the paretic side. These abnormal patterns are likely due to compensations and altered sensorimotor integration processes.

Abrégé

L'Échelle d'Équilibre et de Mobilité Avancés (EEMA) a été dévelopée dans le but d'évaluer l'équilibre debout et pendant la marche d'individus ayant subi un accident vasculaire cérébral (AVC). La première étude pilote, menée chez 12 patients avec un AVC et 6 sujets sains, a demontré que l'EEMA a une excellente *fiabilité inter-évaluateur* et une bonne *capacité de distinguer* ces patients des sujets sains.

Afin d'améliorer la distinction entre les patients de plus haut niveau fonctionel et les sujets sains, nous avons entrepris une étude cinématique de la tâche de marcher et tourner la tête. Cette étude a démontré que les patients ont plus de difficulté à *coordoner* la tête, le tronc et le bassin et ont tendance à *dévier* du parcours de marche pendant les rotations de la tête vers le coté parétique. Ces déficits sont probablement liés aux stratégies compensatoires et aux troubles d'intégration sensorimotrice.

CHAPTER 1

BACKGROUND AND OBJECTIVES

Rationale and Objectives

Balance during standing and walking is perturbed by body movements and changes in the environment. Postural adaptations are generated in response to these changes to minimize postural dysequilibrium both prior to or following the disturbance. Inappropriate adjustments may lead to loss of balance or even falls. Recently, we developed the **Advanced Mobility and Balance Scale** (AMBS) as a clinical measure to assess the effectiveness of postural adaptations during changes in external (environmental) and internal (body movements) demands following a cerebrovascular accident (CVA), or a stroke. The following project consists of two studies. The first was a pilot study aimed at examining the AMBS' psychometric properties, such as its interrater reliability and discriminative validity. The second was a kinematic analysis of one of the tasks of the AMBS, **turning the head while walking**. Results from this part of this study can assist in further refinement of the qualitative scoring elements of the AMBS. The objectives of the kinematic analysis were to identify the normal postural strategies used for turning the head while walking and any abnormal strategies associated with a stroke.

Background

Postural adaptations are essential in order to maintain balance during both quasi static postures (such as quiet stance) and more dynamic tasks (such as locomotion). These adaptations occur in response to changes in postural demands which may be due to internal disturbances from voluntary movements of body segments, such as a head or limb movement, or external disturbances arising from changes in the environment, such as from standing or walking on a slope. In order to prevent a loss of balance or even a fall, postural adaptations are generated in anticipation of, during, and following the disturbance. Such adaptations are in part under sensorimotor control. Following a lesion to one or several of the neural components involved, postural deficits may be observed, as reported following a stroke. There is a need for simple clinical outcome measures that assess the quality of postural adaptations following a stroke in order to develop more adequately focused rehabilitation strategies. As well, comparing postural adaptations in stroke and healthy subjects leads to better comprehension of postural control impairments encountered in stroke patients.

Balance deficits post stroke

Stroke is a major health concern worldwide. The incidence of stroke has been estimated to range from 200 to 1000/100 000 across the world (Sudlow and Warlow, 1997; Hankey, 1999). In Canada, 35 000 people are hospitalized for stroke per year (Mayo, 1996), with an associated economic burden of $2.7 billion per year arising from both direct i.e. hospital, physician and indirect costs i.e. short-term and long-term disability (Heart and Stroke Foundation, 1999). Two thirds of individuals survive a stroke, making it a leading cause of serious disability (Mayo, 1996; Bonita et al., 1997; Sudlow and Warlow, 1997; Hankey, 1999). Some studies report that up to 50% of stroke survivors do not achieve complete functional recovery more than three years post-stroke (Jorgensen et al., 1995; Bonita et al., 1997; Stineman et al., 1997). Decreased independent living is a frequent consequence of stroke. For instance, 20% of people with incomplete recovery go on to require care for at least one activity of daily living. Furthermore, 50% of stroke survivors have difficulty walking outside the house, doing the shopping or taking a bath (Bonita et al., 1997; Tennant et al., 1997). Elderly stroke survivors are more than twice as likely to fall than elderly individuals in the community. Indeed, studies report that up to 73% of stroke patients fall at least once in the first 6 months following discharge, and as many as nearly half of these fall at least twice (Forster and Young, 1995). Falls with injuries frequently result in decreased level of physical activity (King and Tinetti, 1995). However, even falls that do not lead to injury may cause decreased social activities and loss of independence (Shumway-Cook et al., 1997; Tinetti and Williams, 1998). Falls with or without injuries have also been associated with substantial increases in annual health care costs (Rizzo et al., 1998). There is a consensus in the literature that balance difficulties are an important consequence of stroke which affects the patient's level of function and independence. The following sections describe the current knowledge concerning normal postural control mechanisms, and the impact of stroke on these mechanisms.

Postural control in normal humans

Postural control mechanisms

In standing, the goal of postural control is to maintain the projection of the body's centre of gravity inside the base of support, which is the area delineated by the feet. Stability is challenged by the execution of voluntary movements such as reaching for a glass, referred to as *internal disturbance.* Stability may also be disturbed by a perturbation originating from the outside environment such as standing on an icy surface or standing on a moving bus. Such perturbations may be expected or unexpected and are termed *external disturbances.* In order to prevent a fall, these situations require that postural control mechanisms stabilize the body and regain equilibrium by returning the body to its original posture with the centre of gravity inside the base of support (Shumway-Cook and Woollacott, 1995).

During voluntary movements, two types of postural control mechanisms are coordinated by the central nervous system (CNS). First, prior to and during the movement (e.g. reaching with the arm), postural muscles in other body parts are activated. These postural responses, known as *anticipatory postural adjustments (APA)*, are generated primarily through feedforward mechanisms based on previous experience (Horak et al., 1984; Bouisset and Zattara, 1987; Frank and Earl, 1990; Ghez, 1991; Layne and Abraham, 1991; Massion, 1992; Bennis et al., 1996) and an internal representation of the body (Gurfinkel et al., 1988; Merfeld et al., 1993). Lower limb muscles (Cordo and Nashner, 1982; Horak et al., 1984; Bouisset and Zattara, 1987; Frank and Earl, 1990; Rogers and Pai, 1990) and the superficial trunk muscles erector spinae, external oblique and rectus abdominus (Hodges et al., 1999) are activated prior to voluntary arm and leg movements. APA muscle activation onset and amplitude, along with the pattern of muscle recruitment, varies depending on the mass of the segment moved and the velocity at which it is moved, as well as the direction of the movement and its complexity, such as a bilateral versus unilateral task (Cordo and Nashner, 1982; Horak et al., 1984; Bouisset and Zattara, 1987; Frank and Earl, 1990; Rogers and Pai, 1990).

During and following execution of the main movement (e.g. reaching), *compensatory postural reactions* occur to ensure that equilibrium is maintained. These require a feedback control system involving the input and integration of visual and vestibular information, as well as cutaneous and proprioceptive information from the neck, trunk and limbs, and giving rise to the output of corrective motor responses in the neck, trunk and limbs (Bouisset and Zattara, 1987; Frank and Earl, 1990;

Ghez, 1991). During this same time period, APAs are once again generated in anticipation of the expected effect that the compensatory reaction will have on balance, until balance is regained (see Horak and Macpherson, 1996 for review).

With respect to changes in external or environmental demands that can be predicted, such as when approaching a slope, postural control mechanisms are also required. In other words, APAs based on previous experience prepare the person for the external change and both APAs and compensatory postural reactions will be generated to maintain stability while the disturbance persists (Ghez, 1991). Unexpected external disturbances, such as from movement of the support surface, also require postural adaptations. However, as the present study focuses on *expected internal* and *external* disturbances, the effect of unexpected external disturbances is not reviewed.

Postural control during locomotion

Although walking is a common daily activity involving balance, the interaction between postural control and locomotion has not been extensively studied. Postural control during locomotion differs from standing in several ways. As described above, the goal of standing is to maintain the body's centre of gravity within the base of support; during a disturbance, postural control mechanisms act to regain stability. In contrast, the goal during walking is to move the centre of gravity ahead of the base of support when starting or advancing, and within the base of support when stopping (Winter, 1991). Therefore, depending on whether a disturbance occurs during locomotion, postural control mechanisms will act to ensure forward progression from one point to another or to attain stability when stopping.

Adaptations during walking differ from those during standing because of the different goal of the two tasks. For example, forward trunk inclination of healthy subjects increases progressively as the slope increases during uphill walking to propel the body forward, and decreases progressively as the slope increases during downhill walking to control forward momentum of the body. In contrast, the trunk remains vertical in spite of progressively inclined slopes during standing (Leroux et al., 2002). In healthy humans, strategies of postural control during walking also vary depending on the phase of the gait cycle (Nashner and Forssberg, 1986; Hirschfeld and Forssberg, 1991; McFadyen and Carnahan, 1997; Tang and Woollacott, 1999). When healthy subjects perform arm movements during walking, patterns and timing of muscle activation depend on the goal of the task (push or pull) and the phase of the gait cycle during which the arm movement is performed, since the internal representation of the body changes continuously. To summarize, the aim of postural adjustments during walking is to minimize the perturbation to balance due to internal and external disturbances, so as to continue forward progression as fluidly as possible (Nashner and Forssberg, 1986; Hirschfeld and Forssberg, 1991).

Regarding internal disturbances, the effect of **moving the head while walking** has only begun to be studied recently, although it is a common task and one of the criteria for independent community ambulation (Shumway-Cook and Woollacott, 1995). Postural control adjustments to head movements differ from those for limb movements in that they involve the integration of more extensive vestibular, visual and neck proprioceptive inputs that arise during a head turn. Furthermore, during walking, head and eye positions are involved in steering, possibly in part for scanning the upcoming area of travel (Grasso et al., 1996; Grasso et al., 1998; Patla et al., 1999; Vallis et al., 2001). Thus, additional mechanisms may impact the postural adjustments generated in response to a head turn during locomotion. To date, studies examining head turns during forward walking have used passive head movement protocols (Vallis and Patla, 2001; Vallis et al., 2001). When the head movement is voluntary, anticipatory postural adjustments are generated in addition to compensatory postural reactions, to minimize the disturbance. We have therefore conducted studies exploring the effect of *voluntary head turns* during walking. Although healthy young subjects may be able to execute fast head turns during walking with few changes in the kinetic and kinematic profiles of locomotion, we anticipate that postural adjustments may be required with age, and may be inadequate following a neurological lesion such as a stroke.

A common expected external disturbance is a change in surface inclination such as walking uphill or downhill. During slope walking, the step length, lower limb positions and patterns of muscle activity in lower limb muscles of healthy subjects are modified as compared to overground walking (Patla, 1986). When walking uphill on a treadmill, healthy subjects demonstrate increased flexion at the hip, knee and ankle at initial contact compared to level walking (Leroux et al., 1999). As well, trunk forward inclination progressively increases or decrease as the slope changes during uphill or downhill walking respectively (Leroux et al., 2002). However, postural adaptations to inclined surfaces have only been studied in treadmill walking. Treadmill walking is different from overground walking in that there is the additional constraint of a gait speed imposed by the treadmill and the visual surrounding is unnaturally stable. Although the biomechanics of walking have been shown to be similar between treadmill and overground locomotion in healthy subjects (Arsenault et al., 1986), the patterns may be very different in stroke patients. Thus, postural strategies may differ between treadmill and overground walking, and conclusions drawn from treadmill studies might not be applicable to overground walking. As with voluntary movements, it is important to identify the postural strategies involved in adapting to inclined surfaces in healthy subjects, and assess the effect of somatosensory deficits on these adaptations.

Postural control in stroke

The basal ganglia, cerebellum and supplementary motor area are thought to be responsible for generating APAs. The role of the primary motor cortex in these adjustments is not yet known (Horak et al., 1984; Massion, 1992; Bennis et al., 1996). Compensatory postural reactions are thought to be generated in part by the motor and somatosensory cortices, brainstem, thalamus, spinal cord and cerebellum (Frank and Earl, 1990; Ghez, 1991). It is expected that lesions to one or more of the structures involved in postural adaptation are therefore likely to produce some degree of postural control deficits, as observed following a stroke.

Little is known on the extent to which stroke impacts on postural adaptations to both internal and external disturbances during stance and locomotion. For example, healthy and hemiparetic subjects were instructed to drop a load from one hand to the other while sitting, thus creating an external predictable disturbance (Bennis et al., 1996). The APA electromyographic (EMG) activity was of lower amplitude and occurred later in hemiplegic subjects compared to healthy controls. Similarly, activation of postural muscles in the lower limb while performing rapid arm raises during standing are delayed in stroke patients as compared to healthy subjects (Horak et al., 1984). Along the same lines, stroke patients performing standing leg lifts had delayed activation of gluteus medius on the paretic flexing limb to the extent that it no longer preceded knee flexor activation (Hedman et al., 1997). The vertical ground reaction forces generated during paretic and non-paretic leg lifts in stroke patients were also delayed and diminished (Rogers et al., 1993). These studies suggest that the timing and magnitude of postural adaptations following a stroke may be insufficient to prevent or compensate for a disturbance. No studies examining the effect of internal or external disturbances during locomotion in the stroke population have been conducted. There is a need to investigate the impact of stroke on postural adaptations, in order to have a better understanding of stroke-related postural control deficits during walking.

Postural control measures

The primary goal of rehabilitation in stroke is to maximize the patient's functional independence at home and in the community. The importance of postural control and mobility in independent living are well recognized and are therefore an important focus in rehabilitation (Wade et al., 1983; Bohannon, 1987; Dettmann et al., 1987; Turnbull et al., 1996). Outcome measures of postural control and mobility must be reliable and valid in order to detect specific deficits and enable therapists to select appropriate treatment strategies, assess the effectiveness of rehabilitation interventions and provide preventative strategies. As mentioned above, an important component of postural control is the capacity to anticipate and adapt to both *internal* and *external* disturbances during *standing* and *walking*. To our knowledge, this has not yet been accomplished in existing clinical measures of balance and mobility.

Existing clinical measures

Outcome measures generally assess one or more of the components of the model for the International Classification of Impairments, Disabilities and Handicaps (WHO, 1980). In this classification, "impairment" is defined as a loss, change or abnormality of a mental, psychological, physiological or anatomical structure or function. "Disability" is defined as decreased ability to accomplish an activity in a normal way. Finally, "handicap" is defined as the inability to accomplish a social and familial role considered normal for an individual of similar age, gender and socio-economic background. In this model, impairments cause disabilities, which in turn lead to handicaps. Although it is known that there is not necessarily a linear, one-to-one relationship between these three components, they have generally been thought of as distinct. However, a new version of this classification has recently been presented with the terms “body functions and structure” and “activity” replacing “impairment” and “disability” respectively. As well, the unidirectional link from impairment to disability has been replaced with a reciprocal one, suggesting that body functions and activities are interrelated (WHO, 1999). From the new model it is clear that clinical outcome measures must combine the assessment of both physiologic functions (impairments) and activities (disabilities) in postural control. We have investigated the link between *physiologic function* and *activities* of postural control by concurrently measuring movement patterns and balance during an identical activity, that of turning the head while walking.

A review of existing instruments assessing balance and mobility and their psychometric properties is found in Table 1 below.

TABLE 1. Balance and mobility measures

Measures	Tasks tested *	Reliability[1]	Validity[2]
Chedoke McMaster postural control inventory (Gowland et al., 1995)	sit→stand, step forward onto weak foot, SLS, side-ways braiding, abduction of strong leg, tandem walking, walk on toes	Ir/IR=0.92 TR=0.80 IC=N/R	Construct=0.84 (Fugl-Meyer balance score) Concurrent=0.95 (Fugl-Meyer total score) Predicitve=equations for discharge level
Chedoke McMaster disability inventory (Gowland et al., 1995)	walk indoors (25 m); outdoors, (ramps, rough ground, curbs – 150 m), up and down stairs	Ir/IR=0.98 TR=0.98	Construct=0.83-0.85 (FIM); Concurrent=0.79 (FIM), 0.95 (Fugl-Meyer); Predicitve=no Responsiveness=0.53 (variance ratio)
Berg Balance Scale (Berg et al., 1992a and 1992b; 1995; Wee et al., 1999; see Cole et al., 1994 for review)	sit↔stand, sit and stand unsupported, stand eyes closed, feet together, reach forward, pick up object from floor, look over shoulders, turn 360°, alternate foot on stool, tandem stance, single leg stance	Ir/IR≥0.98 TR=N/R; IC=N/R;	Construct= 0.62-0.94 (Barthel ADL Index and Fugl-Meyer); Concurrent=0.46-0.91 (in elderly clients for postural sway, Tinetti balance subscale, Barthel mobility subscale, Timed Up and Go); Predictive=length of stay, discharge destination, use of walking aid; Discriminative=between stroke patients at home, in rehabilitation or in hospital.
Functional Reach Test (Duncan et al., 1990; Wernick-Robinson et al., 1999)	Reaching forward with arm at 90° flexion	(in elderly people) ir/IR=0.92-0.98; TR=N/R;	Construct=0.71 (sway); Concurrent=0.35-0.71 (gait speed); Discriminative=veterans in rehabilitation and controls, Predictive=<6" predicts falls.
Clinical Test for Sensory Interaction in Balance (Shumway-Cook and Woollacott, 1995)	Stand with feet apart on floor / on foam, eyes open / closed / with dome	Ir/IR=68-100% agreement TR=0.99 (r_p)	Concurrent=0.77 (Fugl-Meyer); Discriminative=healthy and vestibular patients;
Timed balance tests (Bohannon et al., 1993)	Stand feet apart/ together, SLS	TR=0.44-0.82	Concurrent=0.59=0.67
PASS (Benaim et al., 1999)	Stand, SLS, sit↔stand, pick up object	IC=0.95	Construct=0.48-0.73 (FIM,lower limb motricity, sensibility, spatial neglect); Predictive=0.75 FIM at discharge
Fugl-Meyer Assessment (see Cole et al., 1994 for review)	Stand with/ without support, stand on affected/ non-affected leg	TR=0.87-1 IR=no sign. Difference between raters	Concurrent=0.67-0.76 (Barthel)
Balance Master (Liston and Brouwer, 1996)	Static and dynamic shifts of centre of gravity	TR=0.29-0.88	Concurrent=0.1-0.67 (r_k) (Berg), 0.04-0.72 (r_k) (gait speed)
Functional Obstacle Course (Means et al., 1996 and 1998)	12 simulations of tasks with different textures, graded surfaces, stairs, object negotiation	IR=small variability (values not reported)	Construct=differentiate between known groups; Concurrent=-0.73- -0.78 (Tinetti), 0.15-0.24 (postural sway);

TABLE 1. Balance and mobility measures (continued)

Measures	Tasks tested *	Reliability[1]	Validity[2]
Dynamic Gait Index (Shumway-Cook and Woollacott, 1995)	walk (20 ft), change speed, walk and move head side to side / up and down, walk and turn, step over / around obstacle, walk up/down stairs	IR=good in preliminary tests;	Others:N/R
Timed Up and Go (Podsiadlo and Richardson, 1991; see Cole et al., 1994 for review)	Stand, walk 3 m, turn around, walk back to chair and sit down	Ir/IR=0.99 TR=0.99	Concurrent=0.55-0.75 (sway path, gait speed, Berg) (in frail elderly) Discriminative=of level of dependence
Functional Independence Measure (Keith et al., 1987; see Cole et al., 1994 for review)	walk indoors, walk up and down stairs	Ir/IR=0.83-0.96 (in spinal cord injured patients;	Concurrent=0.64-0.76 (Barthel – in spinal cord injured patients); Predictive=burden of care, level of life satisfaction (patients with multiple sclerosis); Responsiveness=21-52% change from admission to discharge (spinal cord injured patients)
Barthel Activities of Daily Living Scale (see Cole et al., 1994 for review)	walk indoors (50 yards), walk up and down stairs	Ir>0.71-1.00;	Concurrent=0.64-0.75 (to upper extremity function and Barthel discharge score) Predictive=living arrangement, length of stay, progress, risk of death in 1st 6 months following admission; Responsiveness= scores higher than 60 indicate improvement over time
Physical Performance Testing (Reuben and Siu, 1990; King et al., 2000)	Putting book on shelf, put on /remove jacket, pick up object from floor, turn 360°, walk 50 ft, stairs	IC=0.79-0.87 IR=0.99 TR=0.88	Construct=0.24-0.47 (heatlh status tests and mini-mental status exam) Concurrent=0.5-0.8 (Tinetti, Katz ADL, Rosow-Breslau); Responsiveness=0.8 (resp. index)
Postural Stress Test (Wolfson et al., 1986; Harburn et al., 1995)	Resist displacement from weight pulley system at the waist	TR=0.83-0.93	Predictive: falls,
Sensory-Oriented Mobility Assessment Instrument (Tang et al., 1998)	Sequence of tests: stand up, gait weaving, reach up, bend down, turn 180°, step on cushion	N/R	Concurrent=0.24-0.53 (r_s) (SOT)
Functional Mobility Assessment Tool (Badke et al., 1993)	Performance of ambulation, includes environmental barriers	IR=0.52-0.97 TR=0.82-0.97 (kappa) IC=0.68	N/R

[1]only standing or walking balance tasks are reported; [2]values reported are in stroke patients unless otherwise specified. ir=intrarater reliability; IR=interrater reliability; TR=test-retest reliability (ICC levels reported for reliabilities unless otherwise specified); IC=internal consistency (alpha levels reported unless otherwise specified); r_p= Pearson correlation; r_s=Spearman correlation; r_k=Kendall's coefficient of agreement; N/R=not reported

Examples of the more commonly used measures are discussed below, along with their strengths and limitations. The *Dynamic Gait Index* is an impairment and disability outcome measure that assesses postural control during locomotion only (Shumway-Cook and Woollacott, 1995). Its validity has not been established. Furthermore, it includes tasks that are not feasible for many patients. For instance, walking with continuous back-and-forth head movements up and down, or right and left often makes patients and even healthy individuals dizzy.

The *Functional Reach Test* measures the distance achieved during forward reaching in standing (Duncan et al., 1990). It has been proposed that the choice of movement strategy, i.e. movement at the hips or ankles, should be assessed (Wernick-Robinson et al., 1999). This would combine the assessment of impairment and disability. It was suggested that patients would minimize the displacement of their centre of gravity through different leg and trunk movement strategies, such that they may reach a large distance with their arm without a large displacement in the centre of gravity. Unfortunately, no consistent use of certain strategies among subjects with balance impairments were identified (Wernick-Robinson et al., 1999). Moreover, this test only assesses one aspect of postural control, namely standing while performing a voluntary movement.

The *Chedoke-McMaster Stroke Assessment* (Gowland et al., 1995) contains an impairment and a disability section which assess these aspects using different tasks. However, it is now understood that there is often no clear boundary between the domains of impairment and disability. The postural control inventory contains a series of tasks to be accomplished to reach a certain stage of recovery, but each task is either achieved or not, so that the postural strategies used for each task are not assessed.

The *Berg Balance Scale* (BBS) is a well validated and reliable instrument commonly used in Canadian physiotherapy departments (Berg et al., 1992a; Berg et al., 1992b; Berg et al., 1995; Wee et al., 1999). This is a measure of disability originally developed for a geriatric clientele. The BBS likely has a ceiling effect because at 3 months post-stroke, 70% of patients have been reported to have high BBS scores (Mayo et al., 1999) even though as many as 73% of patients fall in the first 6 months post-stroke (Forster and Young, 1995). Therefore, stroke patients often achieve a high score on the BBS following some recovery, but may still have significant balance deficits.

The *Clinical Test for Sensory Interaction in Balance* is one of the only measures to assess the integration of sensory inputs (i.e. visual, proprioceptive, vestibular) for postural control (Shumway-Cook and Woollacott, 1995). However, it assesses only one aspect of postural control, standing with changes in environmental conditions (e.g. standing on foam or moving visual surround), and provides a measure of sway based on observation alone.

The *Timed Up and Go* is a fast and simple mobility assessment which involves standing up form a chair, walking 3 meters, coming back to the chair and sitting down. The time taken to complete the test is recorded. Although the time taken has been correlated to some balance measures, it does not provide information regarding the cause of the increased time.

In summary, 2 main problems arise from existing postural control outcome measures:

(1) the available scales do not assess postural adaptations to changes in *internal* and *external* demands during *standing* and *walking*;

(2) these scales do not assess both the impairment aspect (i.e. quality of the task) and disability aspect (i.e. ability to do the task) and their interaction in postural control.

The Advanced Mobility and Balance Scale

The *Advanced Mobility and Balance Scale* (AMBS) was consequently developed by our team of rehabilitation experts in the field of postural control and locomotion (Kairy et al., 2000). It consists of 2 categories of tasks performed during standing and walking with respect to: i) internal disturbances (voluntary movements); ii) external disturbances (environmental changes). Each item is scored on a 4-point ordinal scale (0-3; see Appendix 1).

The voluntary movement selected is a single fast head turn to the right, left, up or down. This task differs from the head rotation task of the

Dynamic Gait Index, where repeated head rotations are done. The task in the AMBS is representative of a functional task (e.g. grocery shopping, turning your head when crossing the street). The extent to which head movements interact with postural control has not yet been established. However, it is highly probable that head movements constitute an important perturbation to balance in standing and walking because of the extensive additional sensory input from the eyes, neck and vestibular sensors during such movements.

The external disturbance selected is a support surface change by using an inclined surface. Walking on a slope requires that postural control and locomotion be coordinated to adapt to the new environment. We expect that while negotiating a slope, postural adaptations are used when approaching the slope to anticipate the change in inclination, to adjust to the change in surface while walking on the slope, and finally to anticipate the change while stepping off the slope (McFadyen and Carnahan, 1997). Therefore, these three phases of walking on a slope (stepping on, maintenance, stepping off) are tested in the AMBS.

The first part of this project is a feasibility study of the use of the AMBS in a stroke clientele and a preliminary look at the scale's reliability and validity. Due to the detailed scoring used in the AMBS, we felt that a feasibility study was needed to assess elements such as ease of learning to use the scale and efficiency in using the scale by physiotherapists, prior to pursuing further development of the scale.

Laboratory measures of postural control

Outcome measures in the form of ordinal scales are widely used by clinicians as they are easy and quick to administer, do not use sophisticated equipment, and do not require complex analyses. However, there exist several laboratory methods for studying postural adaptations that offer greater measurement precision and allow additional variables to be measured and analyzed. Kinematic analysis allows for variables such as joint angles, body segment positions and centre of mass position to be calculated. Kinetic analysis provides information regarding ground reaction forces, joint torques and centre of pressure, for example. Finally, EMG analysis allows for various parameters regarding muscle activation to be analyzed, such as the onset of muscle activity with respect to the disturbance, as well as the pattern and sequence of muscle activation. By identifying the normal kinematic, kinetic and EMG patterns involved in postural adjustments, specific deficits in postural control can be identified in a patient population. As is demonstrated in this study, laboratory and clinical measures can complement each other. In particular, kinematic analyses are useful in refining the descriptive elements of an ordinal scale when these are based on the visual inspection of movement. This approach allows clinical assessment tools to be based on scientific evidence. The second part of this study focuses on the kinematic analysis of one of the AMBS items developed in the first part of the study, that of head turning during walking. Once the normal and pathological strategies have been identified, the descriptive scoring of the AMBS for this task can then be validated and improved.

Specific objectives

Based on our knowledge to date of postural control during internal and external disturbances in healthy adults and stroke patients, two studies were conducted. The first was a pilot study on the feasibility of the AMBS to be used by clinicians in a stroke population and a preliminary assessment of the scale's psychometric properties. The second study was a more in-depth analysis of the movement strategies used by stroke patients during one of the AMBS tasks: *turning the head while walking*.

The specific objectives for the first pilot study of the AMBS were to:

1. establish the feasibility of the AMBS for use by clinicians in a subacute rehabilitation setting;
2. explore the interrater reliability of the AMBS in the subacute stroke population;
3. examine the ability of the AMBS to discriminate between stroke and healthy elderly individuals (construct discriminative validity).

The specific objectives for the movement analysis were to:

1. identify normal movement patterns of the head, trunk and pelvis associated with an internal disturbance (i.e. fast head movements) during walking, and contrast them to those associated with a stroke;

2. determine the extent to which fast head movements affect the footpath trajectory during forward walking in stroke patients as compared to healthy subjects.

CHAPTER 2

A POSTURAL ADAPTATION TEST FOR STROKE PATIENTS

Kairy Dahlia, Paquet Nicole, Fung Joyce

Submitted to Clinical Rehabilitation 2001

Abstract

Objective: To develop the Advanced Mobility and Balance Scale (AMBS), which measures the ability of stroke patients to maintain their balance during voluntary head turns and to negotiate slopes. This pilot project was undertaken to (1) explore the interrater reliability of the AMBS and (2) to determine whether this scale discriminates between stroke patients and healthy elderly subjects.

Setting: Neurological rehabilitation program and research centre at a rehabilitation hospital centre.

Subjects: Twelve subjects with varying levels of motor deficits secondary to a stroke occurring within the past year and six healthy elderly individuals.

Main outcome measures: Scores on the AMBS (0-48); comfortable gait speed over 5 meters.

Methods and materials: Subjects were videotaped while performing the following tasks: 1) standing and 2) walking while executing a rapid sudden head motion in one of four directions (up, down, right, left); 3) standing and 4) walking on a 15° inclined surface (uphill or downhill). The AMBS consisted of a four-point scale (0-3) for each trial of head turn direction and incline. *Interrater reliability*: The videotapes were viewed by a panel of five trained physical therapists who scored each trial for each stroke subject. *Construct validity:* The primary investigator assigned a score for each subject on the AMBS and measured comfortable gait speed over 5 meters.

Analysis: *Interrater reliability:* Intraclass correlation (ICC) ratios were calculated based on a repeated-measures design. *Construct validity:* One-way ANOVAs and post-hoc pairwise comparisons (Tukey's tests) were performed to determine whether there was a difference in scores between different functional-level stroke patients and healthy subjects.

Results: *Interrater reliability:* ICCs for the AMBS ranged from 0.93-0.97 for global as well as slope and head turn subscale scores. *Construct validity:* Mean (± standard deviation) scores for the global score were 45 (± 3) for healthy subjects, 40 (±9) for high functional-level stroke patients and 25 (±11) for low functional-level stroke patients. The AMBS global score and slope scores discriminated between stroke and healthy subjects, and between high functional-level stroke patients and low functional-level stroke patients. Standing with head turn scores did not discriminate between any groups.

Conclusion: The AMBS has excellent interrater reliability and good discriminative capacities. The AMBS provides clinicians with a measure of the quality of the postural adaptations used during internal and external disturbances. Further studies of the AMBS will be conducted in order to provide clinicians with a scale that allows them to focus balance and locomotor training more appropriately for each patient.

Introduction

Stroke is a leading cause of serious disability worldwide. Up to 50% of stroke survivors do not achieve complete recovery even after three years (1). For instance, at least 50% of stroke survivors have difficulty walking outside the house, doing the shopping or taking a bath (2). Furthermore, elderly individuals who have suffered a stroke appear to be at greater risk for falls (3). Decreased independent living is clearly a debilitating consequence of stroke. Therefore, postural control and locomotion retraining are essential components of stroke rehabilitation.

There are several clinical measures available to physical therapists for the assessment of balance or mobility. For example, the Berg Balance Scale (4) is a highly reliable scale composed of 14 items which assess the individual's ability to perform various standing tasks such as standing with feet together, standing with eyes closed, tandem standing, stepping onto a stool and turning in a circle. The therapist observes and rates the patient on a 4-point ordinal scale reflecting the amount of assistance provided and/or the time taken to accomplish the task. The Berg Balance Scale has been validated in stroke patients (5). The Chedoke-McMaster impairment inventory (6) is another clinical measure with high interrater and intrarater reliability and both construct and content validity. The scale classifies patients based on the stage of motor recovery. The postural control component of the inventory consists of lying, sitting and standing tasks ranging from rolling to standing with equal weight bearing to tandem walking.

While postural control during standing tasks may be minimally affected in some stroke patients, this may not be the case during mobility tasks such as walking. The Dynamic Gait Index (7) combines eight walking tasks, such as walking and stopping suddenly and walking with continuous head rotations horizontally and vertically. However, the last two tasks induce dizziness in many healthy subjects.

Two main problems arise in the available outcome measures for postural control and locomotion. First, none of the scales assess the basic adaptive and reactive components of postural control, such as the capacities to adapt and react to both internal and external disturbances during standing and walking. Internal disturbances constantly occur during voluntary movements of body segments, such as raising an arm. Such a movement causes an internal disturbance by displacing the centre of gravity. Therefore, postural muscles other than those used to execute the movement need to be activated both prior to the movement, to prevent the anticipated displacement of the centre of gravity, as well as during and following the movement to correct for any displacement. Muscle activity will vary depending on the task, in order to minimize the loss of balance (8). External disturbances may occur due to changes outside the individual, such as in the environment. This type of disturbance may be predictable or unpredictable depending on the situation. For example, standing on a bus which moves unpredictably requires corrective postural reactions to prevent a fall. The external disturbance may also be more predictable in nature, such as when approaching a slope or stairs. In this case, an individual will anticipate the postural changes required and make any corrective changes necessary to prevent a loss of balance (9).

Another shortcoming of the available scales is that they do not assess the interaction between the impairment and disability components of the tasks used. Such a need was recently recognized by the World Health Organization in the adaptation of the new ICIDH-Beta model (10).

It is in this context that we have developed the Advanced Mobility and Balance Scale (AMBS), which assesses postural control in standing and walking. The AMBS uses relevant daily activities as stimuli for changes in posture and gait. The tasks include a rapid voluntary head movement as an internal disturbance and an external change in the incline of the support surface. A full description of the tasks and instructions for administering the AMBS is found in the Appendix.

Our objectives were to explore the interrater reliability of the AMBS in subacute stroke patients and examine its construct validity, i.e. the ability of the scale to discriminate between known groups of subjects, high functional-level stroke patients, low functional-level stroke patients and healthy subjects.

Methods

Subjects

Twelve (12) patients with a diagnosis of a recent stroke (less than six months) participated in this study. They all had evidence of minimal to severe motor deficits of the lower extremity on the affected side (Chedoke-McMaster (5) leg score of less than 7), and were able to stand for 5 seconds or more without external support (Chedoke-McMaster postural control score of 3 or more). Patients with severe hemineglect or brainstem and cerebellar lesions were excluded from the study. In addition, six healthy community-dwelling elderly subjects were recruited. Stroke and healthy elderly subjects were excluded if they had 1) history of lower extremity musculoskeletal injuries in the past year; 2) psychotropic medications which may affect balance; 3) evidence of polyneuropathy in the lower extremity; 4) dizziness or other symptoms indicative of vestibular impairment; or 5) limited neck range of motion. Stroke subjects were recruited from both the in-patient and out-patient neurology program at the Jewish Rehabilitation Hospital (JRH; Montreal, Canada) and healthy subjects were recruited from the hospital's volunteer department. All subjects signed an informed consent form and a separate authorization form for videotaping approved by the hospital ethics committee.

AMBS

The Advanced Mobility and Balance Scale consisted of four main categories of tasks (A-D below), with a total of 12 individual tasks performed by the subject (see Appendix): 1) standing and turning the head once to the right, left, up or down (total = four tasks; figure 1A); 2) walking and turning the head once to the right, left, up or down (total = four tasks); 3) standing on a slope for 90 seconds facing uphill or downhill (total = two tasks; figure 1B); 4) walking up or down a slope (total = two tasks).

Each task is scored on a 4-point ordinal scale (0-3) reflecting the ability of the subject to perform the task and the quality of the performance. For the overground tasks, a 5-meter walkway was used. For the slope tasks, we used a 15° inclined surface which was 2 meters long, 1.2 meters wide and had a 1-meter flat surface before and after the slope (see figure 1B and appendix).

Video recordings

Subjects were videotaped while performing all the tasks from the AMBS. They were also videotaped during quiet stance and walking, as well as sitting with head rotations to the right, left, up and down, in order for the raters to compare these to performance during the AMBS tasks. The video camera was located 4.3 meters (14 feet) from the side of the slope in order to provide a sagittal view of the subjects. This allowed anterior-posterior sway to be seen clearly. Vertical markings on the wall facing the camera assisted in visualizing the amount of sway (figure 1A).

[figure 1 near here]

Panel of raters

Five physiotherapists working in the neurological rehabilitation programs of the JRH were selected to view and rate the performance of the stroke subjects on the AMBS. Their work experience ranged from one year to 28 years. They were trained to use the AMBS by scoring video recordings of one elderly and two stroke patients. They then viewed the recordings of 10 stroke subjects during six one-hour sessions, during which they individually scored the subjects' performance using the AMBS.

Analysis

Interrater reliability

A repeated-measures ANOVA design allowed the required variances to be calculated, followed by an estimation of the intraclass correlation coefficient (ICC), an index of interrater reliability (11), where:

ICC = variance(subjects) / (variance(subjects) + variance (raters) + variance (errors))

Construct validity

Stroke subjects were divided into two functional levels based on their comfortable gait speed over 5 meters:

a) high functional level = gait speed ≥ 0.7 m/s

b) low functional level = gait speed < 0.7 m/s.

ANOVAs were used to determine whether there was a significant main effect due to group (low functional level versus high functional level versus healthy) on the global score and four task scores (standing with head turns, walking with head turns, standing on slope and walking on slope). A p-level of less than 0.05 was accepted as significant. Post-hoc pairwise comparisons using Tukey's test were then performed to compare the scores of different groups.

Results

Subject characteristics are listed in the Table. Stroke and healthy subjects were not significantly different for age ($p=0.18$). There was a similar number of stroke subjects with right and left hemispheric lesions, despite the fact that subjects with severe hemineglect, commonly associated with right hemispheric lesions, were excluded from this study. Gait speed was significantly different between groups ($p<0.01$), which was consistent with our classification procedure (see analysis).

[table near here]

Interrater reliability

AMBS scores assigned to each subject were consistent among the five raters, as indicated by the high ICC values obtained. Specifically, the ICCs were 0.93 for the head turning tasks, 0.97 for the slope tasks and 0.97 for the global score.

Construct validity

Figure 2 illustrates the mean AMBS scores and standard deviations for stroke and healthy subjects. The global score for healthy subjects was 45±3, 40±9 for high functional-level stroke patients and 25±11 for low functional-level stroke patients. There was a significant difference between groups (high functional-level stroke patients, low functional-level stroke patients and healthy subjects) for the global score on the AMBS. As well, there was a significant difference between groups for walking with head turns, standing on the slope and walking on the slope. As seen in figure 2E, post-hoc comparisons showed a significant difference in global score between low and high functional-level stroke patients as well as low functional-level stroke patients and healthy subjects. There was also a significant difference between low functional-level stroke patients and healthy subjects for walking with head turns (figure 2B). Finally, there was a significant difference between low and high functional-level stroke patients, as well as between low functional-level stroke patients and healthy subjects for standing on a slope (figure 2C) and walking on a slope (figure 2D). There was no significant difference between the three groups for the task of standing with head turns (figure 2A). There was no significant difference between high functional-level stroke patients and healthy elderly subjects for any of the tasks (figures 2A-2E).

[figure 2 near here]

Discussion

Interrater reliability

Interrater reliability reflects the extent to which there is agreement between different raters evaluating the same patient who is performing the same task. Good interrrater reliability is essential if a tool is to be used for clinical or research purposes. ICCs greater than 0.9 are generally considered excellent (11). We found excellent interrater reliability for both the subscale scores (head turning ICC = 0.93 and slope ICC = 0.97) and the global score of the AMBS (global ICC = 0.97). This indicates that the five raters from this study agreed on the AMBS score to assign to a patient. It also suggests that the AMBS has well defined and clear items. It is likely that the training period provided to the raters clarified any uncertainties or ambiguities before the study started. The reproducibility level of the AMBS achieved in this pilot study is comparable to that reported for other commonly used balance scales. For instance, studies that examined interrater reliability of the Berg Balance Scale have reported ICCs greater than 0.98 (4). Similarly, an ICC level of 0.92 has been reported for the interrater reliability of the Chedoke-McMaster's postural control score (6). This suggests that adding a mobility element to our scale did not compromise its level of reproducibility.

Construct validity

We found that the global score of the AMBS was significantly different between the three groups of subjects. This indicates that our new scale differentiated between their levels of functioning. As well, the scores for walking on a slope, standing on a slope and walking with head turns were significantly different between groups. However, scores for standing with head turns were not different between groups, suggesting that this task does not discriminate between the different functional level stroke patients and healthy subjects. This observation is compatible with our previous findings that fast head turns while standing induce minimal postural adjustments, as measured from ground reaction forces in healthy elderly subjects (12). One factor that may have led to this finding is that head movement may not cause a sufficiently large displacement of the centre of gravity to require significant postural adjustments in stance with a standard base of support, as used in the AMBS task. Future modifications to the AMBS will necessarily require the task of standing with head turns to be eliminated. It could eventually be replaced by a task requiring more postural adjustments such as head turning during standing with feet together or in tandem.

Results from this pilot study indicate that the tasks may not differentiate well between healthy elderly and high functional-level stroke patients, although high functional-level stroke patients tended to score lower on all the tasks as compared to the healthy subjects. Although several reasons may account for this finding, the small sample size in this pilot study may not have allowed us to pick up any significant differences. As well, the healthy elderly subjects in this pilot study tended to be older than the stroke subjects, although this factor did not achieve statistical significance. The lack of significant difference in scores between the high functional-level stroke patients and the healthy elderly subjects may reflect the effect of aging on balance. Finally, the qualitative descriptors used in the scoring may in fact not be those most affected during these tasks. Therefore, we are currently in the process of conducting a kinematic analysis of the identical tasks in stroke and healthy subjects. Based on our findings, the descriptors will then be modified accordingly.

Further studies of the AMBS psychometric properties and enhancement of the scoring are required so that it may be used clinically and in research to assess postural control during standing and walking in stroke patients. The AMBS will fulfill a need for a clinical measure that may help to not only predict and prevent falls, but also guide rehabilitation interventions. For example, once a task such as walking and turning the head towards the paretic side is identified as destabilizing, it may easily be incorporated into the treatment session. Such clinical measures and focused treatment could ultimately lead to improved quality of life after stroke.

Clinical messages

1. The AMBS is a useful clinical outcome measure of postural control in terms of adaptive and reactive balance capabilities following a stroke.
2. Preliminary results indicate it has high interrater reliability and good discriminative capacities.
3. Using outcome measures with quality descriptors such as the AMBS can help guide specific rehabilitation interventions.

Acknowledgments

We gratefully acknowledge the assistance of Renée Duprat, Laura Galiana, Nigel Heron, Eric Johnstone, Anouk Lamontagne, Caroline Paquette, Anna Phelan-Cox and Jill Tarasuk for this project. We thank Dr. Francine Malouin for her advisory role on Dahlia Kairy's thesis committee. We also thank the volunteer office, patients, and physiotherapists and occupational therapists of the Jewish Rehabilitation Hospital (JRH) for their time and experienced insight. This project was financially supported by the Fonds de la recherche en santé du Québec (FRSQ), the Réseau provincial de recherche en adaptation-réadaptation (REPAR), the JRH Foundation, the Ordre professionnel des physiothérapeutes du Québec (OPPQ), and the Faculty of Graduate Studies and Research of McGill University.

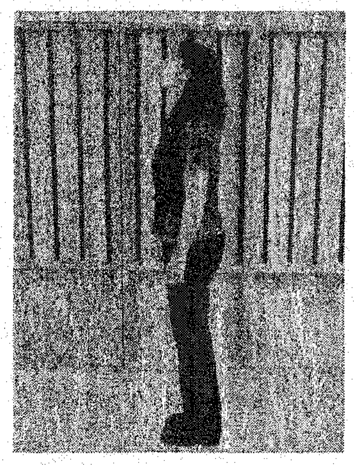
Figure Legends

Figure 1. Examples of a subject being videotaped while performing 2 tasks from the AMBS. A. Illustrates an internal disturbance, standing with head turn up. B. Illustrates an external disturbance, standing on slope facing uphill.

Figure 2. AMBS scores (±1 SD) for high functional-level stroke patients (dark gray columns with upward standard deviation bar), low functional-level stroke patients (black columns with upward standard deviation bar) and healthy subjects (light gray columns with upward standard deviation bar). A. Scores for the task of standing with head turns. B. Scores for the task of walking with head turns. C. Scores for the task of standing on a slope. D. Scores for the task of walking on a slope. E. Global scores.

Figure 1.

A.



B.

Figure 2.

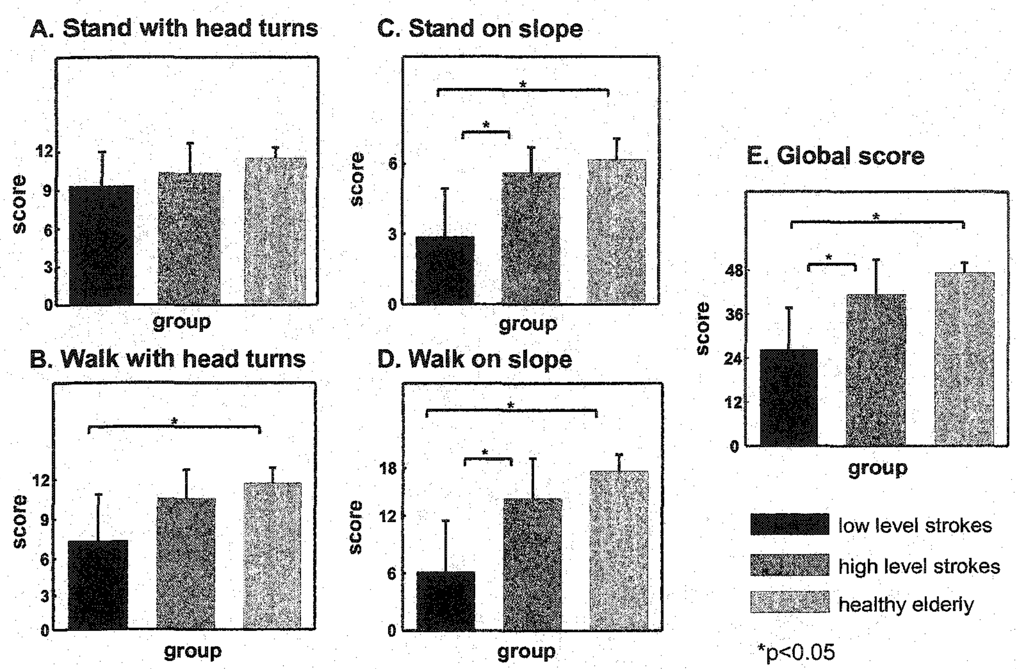

A. Stand with head turns
C. Stand on slope
E. Global score
B. Walk with head turns
D. Walk on slope
score
group
*
low level strokes
high level strokes
healthy elderly
*p<0.05

Table. Subject characteristics

	STROKE			HEALTHY
	low functional level (n=6)	high functional level (n=6)	all strokes (n=12)	healthy (n=6)
Age (mean ± 1 SD)	67.7±10.8	63.3±5.2	65.5±8.4	70.6±7.8
Side of lesion	right=4, left=2	right=3, left=3	right=7, left=5	N/A
Time since stroke (range of days)	60.5 (19-85)	68.8 (22-136)	64.7 (19-136)	N/A
Gait speed (m/s) (mean ± 1 SD)	0.35±0.13	1.14±0.27	0.75±0.56	1.24± 0.06

SD=standard deviation; N/A=not applicable

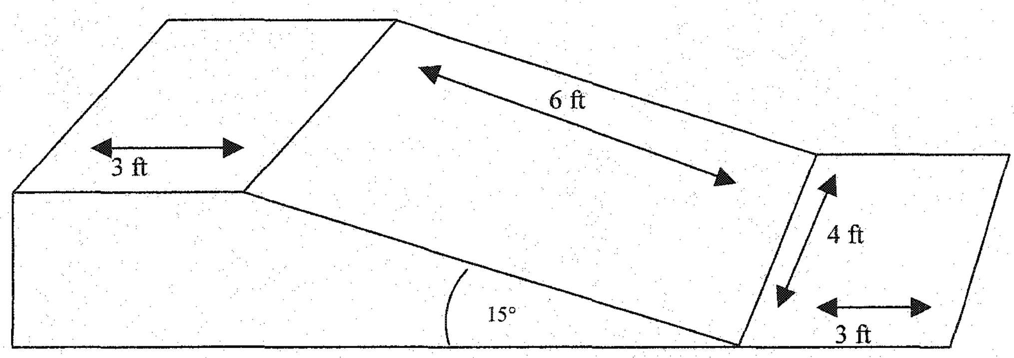
APPENDIX
ADVANCED MOBILITY AND BALANCE SCALE

Researchers:
Joyce Fung PhD, PT; Nicole Paquet, PhD, PT; Martha Visintin MSc, PT.
Jewish Rehabilitation Hospital and McGill University
Dahlia Kairy BSc PT, MSc candidate, McGill University

Objective: This test is designed to assess the capacity of an individual to adapt to perturbations incurred by *internal changes* such as voluntary head movements, and to *environmental changes* such as inclined surfaces during standing and walking

Task Description:
1) Stand and, at the signal, turn head to one of 4 directions (right, left, up or down);
2) Walk on level surface and, at signal, turn head to one of 4 directions (right, left, up or down);
3) Stand for 90 seconds on slope (uphill or downhill);
4) Walk on transitional surfaces (level to up or downhill slope to level surface).

Equipment required:
flat surface (approx. 5 metres)
inclined surface of 15° with flat surface before and after slope (see diagram)
stop watch, plumb line or other vertical reference markings



Minimal functional level required:
Stand for at least 5 seconds without physical assistance (supervision allowed)

Using walking aids: If the subject uses a walking aid on a regular basis it may be used during testing. If needed, the rater can remain by the subject's side without providing any physical assistance. Document the use of any walking aid.
Using orthoses: Test the subject without the AFO if it has recently been prescribed (unless there are strong indications to use it at all times) or if it is only worn for long distances. If the subject complains of discomfort on the slope, the top strap may be loosened during the standing task. Document the use of orthoses.

Scoring:

Four (4) point scale (0-3)

In general:

0 = subject is unable to complete the task without falling or requires physical assistance from the rater to perform the task

1 = subject completes the task but with signs of instability, unsafely or requires supervision

2 = subject completes the task safely but more cautiously than normal

3 = subject completes the task safely and at a normal speed

Task 3 (standing on slope) is a timed task and therefore has a different scale.

One (1) practice trial is permitted per task.

The subject must be compared to his/her baseline unless otherwise specified.

EXCEPTION: If the subject requires physical assistance or supervision during normal walking, score 0 or 1 based on the performance during that task.
e.g.: If the subject requires minimal assistance during normal walking and minimal assistance during walking with head turning, assign a score of 1. Do not score 3 because the subject did not require more assistance than during normal walking.

If there is hesitation between two scores, always score the lowest one.

General definitions:

Physical assistance: Any physical contact provided by the rater to the subject that is required to ensure the subject's safety. If the subject uses a walking aid during the walking tasks, this is not considered "physical assistance".

Unable to complete the task: Applicable if the subject refuses to continue or if the rater decides that the task cannot be performed safely by the subject.

Tasks with head movements (tasks 1 and 2):
Directions of head movements:
1) right; 2) left; 3) up; 4) down.

Active neck range of motion (right/left rotation, flexion, extension) should be measured prior to starting tasks 1 and 2. If the movement of the neck during tasks 1 and 2 is less than 2/3 of the available active range of motion, the rater then scores 0 (i.e. unable to complete the task). There is only one head movement/trial. Therefore, four (4) trials are needed for both tasks 1 and 2.

Task 1: Standing with head movements
Instructions to subject: Stand as straight and as still as you can. When I name a direction, turn your head in that direction as fast and as far as you can. Hold your head in that position until I tell you to bring it back to the middle.

Instructions to rater: Chose a direction (right/left/up/down). Observe the subject during quiet stance and then name the direction of movement. Observe the execution of the movement and the standing position for a few seconds following the head movement as well as following the return of the head to the midline.

Scoring:
0. Unable to complete the task or requires physical assistance
1. Presence of one of the following *signs of instability** following head movement:
    *change in body alignment
    *increased body sway
    *outstretched arms
   or requires supervision
2. Able to perform head movement with no signs of instability* but with caution (slow or guarded)
3. Able to perform head movement quickly and safely with no signs of instability*

Definition:
signs of instability: If you observe one the signs (*) mentioned above, it must be different from that observed for this subject during quiet stance.

Task 2: Overground walking with head movements
Instructions to subject: Walk in a straight line at your normal pace. When I name a direction, move your head in that direction as fast and as far as possible while you continue walking. Keep your head in that position until I tell you to bring it back to the middle.

Instructions to rater: Choose a direction (right/left/up/down). Observe the subject for several steps and then name the direction of head movement. Observe the execution of the movement and the gait following the head movement as well as following the return of the head to the midline.

Scoring:

0. Unable to complete the task or stops walking following head movement or requires physical assistance
1. Fluidity of limb movements is disrupted for 2 or more steps following head movement or requires supervision
2. Fluidity of limb movements is disrupted for only one step following head movement
3. Able to perform the task with no disruption to fluidity of limb movements

Definitions:
stops: Applicable if the subject comes to a complete stop and cannot continue walking or if the subject stops to turn his/her head and then resumes walking.

fluidity of limb movements is disrupted: Changes in gait (step length, amplitude and direction of limb movements at hips, knees or ankles) compared to usual overground walking for this subject

Tasks on inclined surface (tasks 3 and 4)

The tasks involving a slope must be tested both uphill and downhill.

Task 3: Standing on slope

Instructions to subject: Stand as straight and as still as you can on the slope for 90 seconds.

Instructions to rater: Make sure that the subject's feet are sufficiently apart so that the base of support is similar to that on a flat surface. Time the subject for 90 seconds and observe the subject for any signs of instability.

Scoring:

0. Unable to complete the task or requires physical assistance within the first 30 seconds
1. Requires physical assistance after more than 30 seconds
2. Sustains task for more than 90 seconds, but with the presence of one of the following *signs of instability**:
   - *change in body alignment
   - *increased body sway
   - *outstretched arms

   or requires supervision
3. Able to perform task for more than 90 seconds with no signs of instability*

Definition:
signs of instability: If you observe one the signs (*) mentioned above, it must be different from that observed for this subject during quiet stance on a flat surface.

Task 4: Walking on slope

This task is divided into 3 phases:

A) transition from the level surface to the slope
B) walking on the slope
C) transition from the slope to the level surface

Instructions to subject: Walk uphill (or downhill) as you normally would on a flat surface until you reach the flat surface.

Instructions to rater: Place the subject on the level surface in front of the slope, several steps away. Observe the subject until he/she reaches the level surface. If needed, you may walk next to the subject without providing physical assistance.

A. Transition from level surface to slope:
Start: leading foot lands on slope End: trailing foot lands on slope

Scoring:

0. Unable to negotiate change in slope or requires physical assistance
1. Stops or slows down while stepping onto slope or requires supervision
2. Readjusts step (shorten or lengthen) as subject steps onto slope
3. Maintains constant gait speed and step length while stepping onto slope

B. Walking on slope: does not include first and last step on slope
Start: lagging foot touches slope End: before leading foot touches flat surface

Scoring:

0. Unable to complete task or requires physical assistance to walk on slope
1. Fluidity of limb movements is disrupted, with decreased gait speed or requires supervision
2. Decreased gait speed or disruption to fluidity of limb movements
3. Able to walk on slope with no change in gait speed and with no disruption to fluidity of limb movements

Note: gait speed and fluidity of limb movements on the slope must be similar to that observed during walking on the flat surface.

C. Transition from slope to level surface:
Start: leading foot lands on flat surface End: trailing foot lands on flat surface

Scoring:

0. Unable to negotiate change in slope or requires physical assistance
1. Stops or slows down while stepping off slope or requires supervision
2. Readjusts step (shorten or lengthen) as subject steps off slope
3. Maintains constant gait speed and step length while stepping off slope

Definition:

gait speed: During phase C, gait speed is compared to that observed during slope walking immediately preceding this phase and not to that on a level surface.

References

1 Jorgensen H, Nakayama H, Raaschou H, Vive-Larsen J, Stoier M, Olsen T. Outcome and time course of recovery in stroke. Part I: Outcome. The Copenhagen Stroke Study. *Arch Phys Med Rehabil* 1995; **76**: 399-405.

2 Tennant A, Geddes JM, Fear J, Hillman M, Chamberlain MA. Outcome following stroke. *Disabil Rehabil* 1997; **19**: 278-84.

3 Forster A, Young J. Incidence and consequences of falls due to stroke: a systematic inquiry. *BMJ* 1995; **311**: 83-6.

4 Berg KO, Wood-Dauphinee SL, Williams JI. The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. *Scand J Rehabil Med* 1995; **27**: 27-36.

5 Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. *Can J Public Health* 1992; **83**: S7-11.

6 Gowland C, VanHullenaar S, Torresin W, Moreland J, Vanspall B, Barrecca S, et al. *Chedoke-McMaster Stroke Assessment: Development, Validation and Administration Manual.* Hamilton: Chedoke-McMaster Hospitals and McMaster University, 1995.

7 Shumway-Cook A, Woollacott M. *Motor control - theory and practical applications*. Baltimore: Williams and Wilkins, 1995.

8 Massion J. Movement, posture and equilibrium: interaction and coordination. *Prog Neurobiol* 1992; **38**: 35-56.

9 McFadyen BJ, Carnahan H. Anticipatory locomotor adjustments for accommodating versus avoiding level changes in humans. *Exp Brain Res* 1997; **114**: 500-6.

10 WHO. *International classification of functioning and disability*. Geneva, Switzerland: WHO, 1999.

11 Streiner D, Norman G. *Health measurement scales: a practical guide to their development and use.* 2nd ed. Oxford: Oxford University Press, 1995.

12 Paquet N, Kairy D, Fung J. Changes in ground reaction force do not precede fast head turns in standing humans. *Soc Neurosci Abstr* 1999; **25**: 108.

Improving clinical measures using laboratory instruments

Results from the preliminary study of the AMBS' psychometric properties demonstrate that this scale could be understood and used appropriately by physiotherapists in a subacute stroke clientele. However, the descriptive items used in the scoring and their ranking may limit the scale's capacity to discriminate between higher level functioning stroke patients and healthy subjects. This reflects the lack of available knowledge on normal postural adaptation strategies used during these tasks and the effects that sensorimotor deficits have on these strategies. Therefore, a second study involving a detailed movement analysis of the task of turning the head while walking was conducted in healthy and stroke subjects. This study provided a normal baseline on the effect of a fast head turn on gait. In addition, it allowed a comparison of movement strategies used by stroke patients with those used by healthy subjects when performing this task.

CHAPTER 3

KINEMATIC STRATEGIES IN RESPONSE TO HEAD MOVEMENTS EXECUTED WHILE WALKING IN NORMAL AND HEMIPARETIC SUBJECTS

Kairy Dahlia, Paquet Nicole, Fung Joyce

Submitted to Gait and Posture 2001

Abstract

This study examined head-trunk and pelvis-trunk coordination patterns used for voluntary head movements during gait, and the impact of these movements on the forward progression of gait in stroke and age-matched healthy subjects. Head movements during walking were perturbing to the stroke subjects but not healthy controls, causing altered head-trunk and pelvis-trunk coordination. Stroke patients also exhibited a reversal in the direction of deviation during head turns towards the paretic side. It is likely that the sensorimotor integration processes are affected by a stroke. Results from this study are also discussed with respect to a head control mechanism for steering.

Introduction

Balance and locomotion are constantly challenged during daily activities. Sensory inputs and motor outputs must be monitored and modified on an ongoing basis in order to continue walking and avoid falling. Challenges to balance and locomotion may arise from environmental or external factors such as slopes and obstacles as well as from internal demands, such as voluntary limb movements produced by the individual. External factors may be predicted or unpredicted by the individual, such as that imposed by a visible obstacle or a moving bus stopping unexpectedly. In contrast, voluntary movements are always predictable and are preceded by postural adjustments (i.e. anticipatory postural adjustments).[1,2] When internal perturbations arise due to voluntary movements, the interaction of both anticipatory and reactive adjustments is required during ongoing locomotion. That is, the appropriate motor commands and accurate sensory inputs must be integrated to produce precise postural adjustments in order to maintain the smooth, forward progression of the body.

While voluntary movements during static tasks such as standing have been examined, few studies have investigated the interaction between locomotion and voluntary body movements, a combination of tasks frequently required in daily activities. Voluntary movements that could perturb balance during locomotion include movements of the upper or lower limbs, the trunk or the head, and any combination of these.

During such focal movements, the central nervous system likely uses (1) an internal representation of the body's characteristics, (2) the predicted mechanical disturbance that the focal movement will have on balance based on experience, and (3) the proprioceptive, vestibular and visual signals associated with the movement, to generate the postural adjustments needed to maintain balance and continue walking.[1,2] For instance, in the execution of a push-pull movement during treadmill walking, muscle responses in the lower extremities were activated prior to and simultaneously with those in the upper extremity.[3] In addition, these postural adjustments were modulated based on the nature of the task (pull/push) and the phase of the gait cycle.[4] These adjustments must be continuously updated to reflect the changes in mechanical constraints during gait.

Head movements could perturb balance in much the same way as limb movements do. Furthermore, head turns also require the integration of more extensive vestibular, visual and neck proprioceptive inputs that arise during the movement. Moreover, head and eye movements are likely involved in the steering of locomotion.[5,6] Thus, additional locomotor mechanisms may play a role in the generation of appropriate postural adjustments in response to a head turn during walking. Unfortunately, few studies have examined the effect of voluntary head movements on locomotion, although the execution of voluntary head turns during walking is one of the prerequisites for independent community ambulation.[7] The effect of sudden passive head turns on steering during locomotion has been investigated using a head-mounted pneumatic apparatus.[8] Unexpected head perturbations to the right or left were induced just before or as subjects were signaled to steer to the right or left. The head was reoriented towards the direction of steering even during head perturbations away from the direction of steering. This is in agreement with the suggestion that during locomotion, scanning of the upcoming area is essential, so that during steering, head and eye positions are modified first in order to scan the new travel path.[5,6,9]

Postural adjustments generated in response to active head turns likely differ from those arising from passive head movements. During active movements. a motor command and an efferent copy of this command are generated prior to the movement[10] so that appropriate postural adjustments may be made, not only in reaction to the perturbation caused by the head movement, but also in anticipation of the expected perturbation. We have begun a series of studies exploring the effect of voluntary head turns during walking. To date, our preliminary findings in healthy young subjects indicate that the kinematic and kinetic profiles in locomotion are not modified by an active head movement.[11] We anticipate that pathologies causing motor or sensory deficits may lead to inadequate postural adjustments. During voluntary movements, stroke patients have delayed onset of postural adjustments with respect to the focal movement[12-14] as well as delayed weight shifting.[15] Clinical observations indicate that stroke patients often slow down, modify their gait pattern or even stumble when a head turn is performed during walking.[16]

We therefore hypothesize that head turns during walking are more destabilizing to stroke patients than healthy individuals, as indicated by altered body kinematics and abnormal footpath deviations. The objectives of the present study were: (1) to identify the extent to which the head-trunk and pelvis-trunk coordination strategies used for voluntary head turning during gait are altered following a stroke; and (2) to determine whether fast head turns impact on the forward progression of gait in stroke patients, as compared to healthy subjects.

Methods

Subjects

Ten subjects who suffered a cerebrovascular accident (CVA) less than 6 months prior to the study and five healthy subjects of similar ages participated in this study. All the stroke subjects had evidence of minimal to severe motor deficits of the lower extremity on the paretic side (Chedoke-McMaster impairment inventory, leg score[17] of less than 7), and were able to stand for 5 seconds or more without external support (Chedoke-McMaster postural control score[17] of 3 or more). Subjects with expressive and/or comprehensive aphasia (Functional Independence Measure[18] score less than 6 for communication items), severe hemineglect, bilateral cerebral involvement, or brainstem and cerebellar lesions were excluded from the study. Stroke and healthy subjects were excluded if they had: (1) a history of lower extremity musculoskeletal injuries in the past year; (2) were taking psychotropic medications that may affect balance; (3) evidence of polyneuropathy in the lower extremity; (4) dizziness or other symptoms indicative of vestibular impairment; or (5) limitation in neck range of motion. Stroke subjects were recruited from both the in-patient and out-patient neurology program at the Jewish Rehabilitation Hospital (Laval, Quebec, Canada) and all subjects signed consent forms approved by the hospital's ethics committee.

Data Collection

All subjects walked along a 7-meter walkway and were instructed to continue walking while turning their head as soon and as rapidly as possible in the direction indicated by an illuminating arrow placed at the end of the walkway. Subjects wore a harness that was attached to an overhead rail with linear bearings to allow smooth progression and prevent falls. They were always closely followed by an assistant. No subjects used walking aids during the testing, but ankle-foot orthoses were worn by 2 patients due to ankle instability. On average, three trials with arrows signalling to the right, left, up or down and six trials with no arrow were presented randomly at right initial heel contact for healthy subjects and initial paretic foot contact for stroke subjects. For clarity, head turns executed towards the paretic side are reported as ipsilateral (ipsi) head turns, and those away from the paretic side are contralateral (contra).

Three-dimensional (3-D) body segment positions were recorded using 23 retro-reflective markers placed on anatomical landmarks on the head, trunk, pelvis and lower limbs and by a 6-camera Vicon motion analysis system (Vicon 512; Oxford Metrics Ltd) at a sampling rate of 120 Hz. The data was low-pass filtered at 10 Hz using a 2^{nd} order dual-pass Butterworth filter, based on previous residual analyses using the method recommended by Winter.[19] Data were analyzed using BodyBuilder (Oxford Metrics Ltd), Matlab (MathWorks Inc) and Statistica (StatSoft Inc) softwares.

A global coordinate system, such as that described by Winter[19] was established, with the negative X-axis being the direction of progression, the positive Y-axis being the mediolateral direction towards the right, and the positive Z-axis pointing vertically upwards (see figure 1). Local frames of reference were set up for the head, trunk and pelvis segments. Each of these segments was defined using three non-colinear markers as follows:

head: right and left temple and a midpoint at the back of the head;

upper trunk: right and left acromion process tip and C7 spinous process;

pelvis: right and left anterior-superior iliac spines and sacrum (S1).

[figure 1 near here]

Data Analysis

A gait cycle was defined as the period from one initial foot contact to the next. The paretic limb of a stroke patient and the right limb of a healthy subject were used as the referent limb in normalizing to the gait cycle. Dependent variables are reported for the gait cycles during and after arrow presentation. The two-way ANOVA (see statistical analysis below) showed no significant difference between right and left head turn displacement or between right and left head turn velocity so that in some instances variables for right and left head movements were averaged as horizontal. Similarly, variables for up and down head movements were averaged as vertical as there were no significant difference between up and down head movement displacement or between up and down head movement velocity.

Dependent variables:

1) Kinematic variables:

a) segment coordination patterns: comparison of 3-D angular displacements for head on trunk and pelvis on trunk in the same plane as the direction of head movement;
b) segment excursions: range of angular displacement of the head, trunk and pelvis in 3 planes about the x, y, and z axes over entire gait cycle;

c) excursion ratios (ER):

head on trunk ERs:

flexion: head flexion excursion / trunk flexion excursion

rotation: head rotation excursion / trunk rotation excursion

pelvis on trunk ERs:

flexion: pelvis tilting excursion / trunk flexion excursion

rotation: pelvis rotation excursion/trunk rotation excursion

d) footpath variables: obtained from the right and left 2nd toe trajectories (see figure 2). In order to obtain a measure of lateral foot placement, the step length was normalized by dividing each gait cycle into 10 equally spaced intervals. The variables analyzed are:

i) *lateral position path* (in meters): difference between position of the right and left toe in the y-axis at each of the 10 gait cycle interval;

ii) *head turn deviation path* (in meters): difference between lateral position during trials with and without head turns at the same gait cycle intervals;

iii) *symmetry index*: difference between area covered by each foot per gait cycle for trials with and without head turns.

[figure 2 near here]

2) Gait speed (in meters/second): measured using a midpoint between the left and right anterior superior iliac spine markers, which represents a point close to the centre of mass position during standing. Two different components of gait speed were analyzed:

a) instantaneous: change in position of the midpoint per one second time interval; obtained from the 1st derivative of the displacement of the midpoint in the X axis;
b) overall: mean instantaneous gait speed over entire walking trial

Statistical analysis

Two-way ANOVA's were used to test for differences between the two groups of subjects (patients versus healthy) and the 5 directions of head turn (right, left, up, down, none); Tukey's post-hoc pairwise comparisons were conducted on significant differences. As well, comparisons were carried out on subgroups of right and left hemiparetic stroke patients for some variables, as described in the results.

Results

Subject Characteristics

Ten CVA subjects (8 men, 2 women; 5 right CVA, 5 left CVA; mean age 66.1 years old) participated in the study. Table 1 shows that the overground comfortable gait speed as measured in the clinic ranged from 0.12 m/s to 1.21 m/s, and that other clinical balance scores clustered around the higher end of the scales. Five healthy subjects (3 men, 2 women; mean age 66.6 years old) with gait speeds ranging from 1.05 to 1.5 m/s also participated.

[table 1 near here]

Basic characteristics of head movements and gait

Typical head range of motion and head angular velocity traces are presented in figure 3A for one stroke and one healthy subject. Figure 3B shows group mean head range of motion and head angular velocities. Horizontal head turns were symmetrically executed in healthy and stroke subjects. Vertical head movements and the corresponding angular velocities were significantly smaller than horizontal ones for all subjects ($p<0.01$). Although stroke patients executed head turns with similar ranges of motion, angular velocities were significantly reduced for all head turn directions as compared to healthy subjects ($p<0.0001$). Onset of head turns occurred during the stance period, with the majority during the single support phase of the paretic limb for stroke patients or the right limb for healthy subjects. The remainder occurred either during the first or second period of double support.

[figure 3 near here]

Mean overall gait speed as measured during the testing session ranged from 0.43 to 0.48 m/s in stroke subjects and 1.30 to 1.33 m/s in healthy subjects. Gait speeds were significantly slower in stroke patients as compared to healthy subjects ($p<0.001$). All left hemiparetic subjects had slower gait speeds than right hemiparetic subjects. For both groups of subjects, gait speed did not significantly change in the step following the head turn as compared to the preceding step, and it was similar for all head turn directions.

Segment excursions

Figure 4 compares the excursions of the head and trunk for stroke and healthy subjects during trials with horizontal and vertical head movements and trials without head turns.

[figure 4 near here]

Head excursion

Head flexion-extension excursions were significantly larger in healthy as compared to stroke subjects for vertical head movements (see Figure 4A; $p<0.02$). Mean values (± 1SD) were about 10° smaller in stroke (39.0°±10.3°) as compared to healthy subjects (49.5°±4.2°) performing vertical head movements. Head rotation was similar in stroke (57.8°±10.3) and healthy subjects (66.5°±8.7) during horizontal head turns.

During vertical head turns, small rotations of 7.7°±1.0 for healthy subjects and 8.8°±3.8 for stroke subjects were observed (see Figure 4A). Similarly, during horizontal head turns, small vertical movements of 8.5°±2.6 and 10.6°±3.9 were recorded for stroke and healthy subjects respectively. Therefore, head movements, whether horizontal or vertical, were slightly diagonal. For example, head movements up had a small horizontal rotation component.

Trunk excursion

Trunk flexion-extension excursions during vertical head movements were 9.8°±1.8° for stroke subjects and 15.4°±3.3° for healthy subjects performing vertical head movements Trunk rotation excursions were 17.9°±3.0° for stroke subjects and 23.9°±4.8° for healthy subjects during horizontal head turns (Figure 4B). As well, there were associated trunk flexion movements during horizontal head turns and trunk rotations during vertical head movements. Unlike head excursions, there was no significant difference in trunk excursion between groups for any head turn direction.

Pelvis excursion

Stroke subjects had on average 19% more anterior-posterior pelvis tilting ($p=0.04$) than healthy subjects during trials with and without head turns (vertical head movement: 7.1°±2.1° versus 5.8°±0.7°; horizontal head turn: 6.4°±2.2° versus 5.3°±0.7°; no head turn: 6.9°±2.3° versus 5.4°±0.9° for stroke versus healthy subjects respectively). In contrast, stroke subjects had on average 17% less pelvis rotation than healthy subjects during all trials (vertical head movement: 10.9°±3.0° versus 13.9°±6.7°; horizontal head turn: 13.5°±3.7° versus 15.1°±6.0°; no head turn: 11.6°±3.1° versus 14.0°±7.7° for stroke versus healthy subjects respectively). Trials with and without head turns did not produce different pelvis excursions for any group.

Segment coordination

Table 2 lists the Excursion Ratios obtained for head versus trunk excursion as well as pelvis versus trunk excursion. They are reported in order to describe the movement of one segment relative to the other. Ratios greater than one reflect larger head or smaller trunk movements for head-trunk ratios, while they reflect smaller pelvis or larger trunk movements for pelvis-trunk ratios.

[table 2 near here]

Head-trunk coordination

As expected, head on trunk flexion ER were largest in stroke (3.8) and healthy subjects (3.9) during vertical head movements, while rotation ratios were largest during horizontal head turns for stroke (3.2) and healthy subjects (3.5) as compared to other head turn directions ($p<0.001$; see gray areas in Table 2). Surprisingly, head on trunk flexion and rotation ERs were similar in stroke (0.5-3.8) and healthy subjects (0.6-3.9) for all head turn directions. However, the coordination and sequencing of segment movement differed in the two groups, as demonstrated in Figure 5A. This figure illustrates movement of the head and trunk segments in the same plane during one typical trial of each head turn direction. Perfectly horizontal tracings during right and left head turns and vertical tracings during up and down head movements would indicate that no trunk movement occurred during the head turn. Perfectly vertical tracings during right and left head turns and horizontal tracings during up and down head movements would indicate that only trunk movement occurred. Diagonal tracings indicate concurrent head and trunk movements either in the same direction or opposite direction as specified by the axes on the graphs. Healthy subjects executed all head turns with a period of trunk stability followed by concurrent trunk movement in the same direction as the head movement (Figure 5A, uppermost graph). In contrast, stroke subjects had less trunk stability and did not only move the trunk in the same direction as the head movement, i.e. head-trunk movements were more dissociated. The two lower graphs in figure 5A demonstrate the variability in coordination patterns between two stroke subjects of different functional levels. Lack of smoothness in the trajectory and increased oscillations at the end of movement was also evident in the two stroke subjects as compared to the healthy subject.

Pelvis-trunk coordination

For all subjects, flexion ER were smallest during vertical head movements, as compared to other head turn directions for stroke (0.7) and healthy (0.5) subjects ($p<0.02$; see gray areas in Table 2). This is likely due to similar anterior-posterior pelvis tilting during all head turn directions but increased trunk flexion-extension during vertical head motions. Rotation ER were smallest during horizontal head turns as compared to other head turn directions ($p<0.03$). Pelvis on trunk rotation ER during head turn trials were significantly smaller in stroke subjects (0.9-1.1) as compared to healthy subjects (1.7-1.8; $p<0.01$; see gray area in Table 2), during horizontal and no head turn trials, likely due to the 17% reduction in pelvis rotations in stroke subjects.

Most stroke patients had pelvis instability in the sagittal (8/9) and horizontal (7/9) planes for all head movement directions, as is apparent from the continuous fluctuations in pelvis movement during the gait cycle illustrated in Figure 5B (two lower graphs). In contrast, healthy subjects maintained the pelvis stable relative to the trunk for varying lengths of time during the gait cycle for all head movement direction (Figure 5B, uppermost graph).

[figure 5 near here]

Footpath

Lateral foot position and head turn deviation

Figure 6A illustrates the average lateral foot position path of healthy subjects and right and left hemiparetic patients during walking trials with no voluntary head movements. These traces were subtracted from those with head turns to obtain the deviation induced by head turns. Figure 6B demonstrates that horizontal head movements produced significantly larger medio-lateral deviation of the foot path trajectories than vertical head movements in all subjects ($p<0.01$).

[figure 6 near here]

Symmetry of foot position during horizontal head turns

Symmetry indices (SI) represent the surface area covered by each foot during one gait cycle with respect to a midpoint between the two feet at the beginning of the first gait cycle. Negative values indicate area covered to the right and positive values indicate area covered to the left of this midpoint. Symmetry Indices (SI) in figure 7 show that healthy subjects generally deviated towards the direction of the horizontal head turn, and this increased during the second step towards this same direction. In contrast, during head turns to the paretic side, stroke subjects actually reversed directions, first deviating away from (positive SI values) and then towards (negative SI values) the paretic side. There was a significant interaction effect between group (stroke and healthy subjects) and head turn direction (right and left; $p<0.03$).

[figure 7 near here]

Discussion

Following a stroke, head turning is more perturbing to locomotion than in healthy individuals. For instance, stroke subjects manifested altered head-trunk and pelvis-trunk coordination patterns while executing head movements during walking. Moreover, while stroke subjects did not adjust their gait speed, they had slower head movements and a reversal in lateral footpath deviation. These changes may be due in part to deficits in the motor and sensory systems and inappropriate or delayed postural adjustments.

Altered head-trunk and pelvis-trunk coordination patterns in stroke subjects

In general, stroke patients showed a spectrum of coordination patterns ranging from near normal to total discoordination. Stroke patients had difficulty maintaining trunk stability and the trunk movements were not necessarily in the same direction as the head movement. As well, stroke subjects had increased pelvic tilt excursions and decreased pelvic rotation as compared to healthy subjects. The majority of patients were unable to maintain the pelvis stable with respect to the trunk during head turns. The segment excursions and coordination patterns indicate that the head turn has a more generalized effect on the body affecting multiple segments in stroke patients. These findings suggest that the perturbation from the head turn is likely well compensated for in healthy adults at the level of the trunk and does not require further adjustment at the level of the pelvis. In contrast, stroke patients may inappropriately compensate for the perturbation from the head at the level of the trunk, thus requiring further compensation at the pelvis or more distal segments.

Decreased head velocity during head turns executed while walking in stroke subjects

Healthy subjects executed horizontal head turns with larger amplitude and greater velocity than vertical head turns. The patient group followed this same pattern but it had lower peak head angular velocities (117-221°/sec in stroke versus 217-365°/sec in healthy subjects for all head turn directions). On the other hand, stroke subjects are able to perform head movements at velocities close to those of healthy subjects during tasks of lower postural demands, such as sitting and standing (not shown). These findings are in line with those obtained in hemiparetic patients, where arm raises on the non-paretic side were executed with slower velocities and accelerations than healthy subjects.[12,21] Lower head velocities in patients may reflect the inability to perform higher velocity movements during this task due to an impaired motor control system. It may also suggest that stroke patients select this strategy to limit the extent of the perturbation to locomotion so that they can adapt to the perturbation safely. The latter suggestion is further supported in this study since all subjects maintained their comfortable gait speed with and without voluntary head movements, evidence that progressing the body in space is prioritized over executing the fast head movement.

Reversal of lateral footpath deviation during head turns to the paretic side in stroke subjects

Larger medio-lateral gait deviations were observed during voluntary horizontal head turns as compared to vertical head movements in all subjects, indicating that horizontal head turns were more disturbing to forward locomotion. The larger range of motion and angular velocity of the horizontal head turns may in part explain the larger gait deviations we reported during these head movements. We also found that healthy subjects deviated towards the direction of head turn. Previous studies of steering during walking reported that, prior to initiating a change in the direction of travel, gaze is directed towards the intended direction, followed by head movement in the same direction.[5,6,9] Even when the head is immobilized, the trunk is oriented to the direction of travel to reorient the gaze, although the travel path could be scanned through eye movements alone.[22] These studies propose that head position in space is an important parameter controlled by the central nervous system during steering. It has previously been suggested that a feedforward control mechanism is used during steering whereby eye reorientation to the travel path occurs first, and is followed by head reorientation and then body movement.[5,8,9,22,23] Although the present study paradigm dictated a forward progression path, the head turn itself induced movement of the whole body and a change in direction, similar to that seen during steering. We found that healthy subjects had larger footpath deviations in the step following the head turn, indicating that subjects found it harder to maintain a straight path when the head was rotated for longer periods of time. Thus, healthy individuals may only be able to override the effect of head position on travel direction to a limited extent. Further studies need to be conducted to determine the extent to which this feedforward control mechanism can be overridden.

We also found that stroke patients manifested a reversal in the lateral deviation of the footpath trajectory during head turns towards the paretic side. That is, they deviated first away from and then towards the paretic side during these head turns. These results indicate that stroke patients had more difficulty controlling forward locomotion during head turns towards the paretic side. This may suggest that, following a stroke, the sensorimotor integration processes are affected to a different extent in response to inputs from head turns to the paretic and non-paretic side. Several studies have suggested that head-trunk coordination during normal locomotion plays a role in maintaining gaze stability.[24-26] As well, gaze stability plays an increasingly greater role in balance during tasks that produce large postural instabilities.[23] Many factors are involved in maintaining this head-trunk coordination, including bilateral vestibular and cervical feedback inputs, voluntary mechanisms and viscoelastic properties of the head, neck and trunk.[26] During an active head movement, these factors must be appropriately regulated on both sides in order to readjust gaze. Although the design of this study did not allow us to examine gaze during the head turn, it is plausible that the voluntary and feedback control in stroke patients may be inappropriate on one or both sides to restabilize gaze efficiently, thus leading to poorer balance during the head turn. This may also provide additional insight into the feedforward control mechanism linked to head position, which may be altered following a stroke.

The reversal in lateral deviation during ipsilateral head turns may also reflect a larger mechanical perturbation induced by a head turn to the paretic side. Head turns during gait are expected to cause minimal shifts in the body centre of mass due in part to the relatively small mass of the head and its short lever arm with the centre of rotation located at the centre of the head. However, abnormal head-trunk dissociation may lead to greater displacements of the centre of mass during head turning. This might require increased weight bearing on the weaker, paretic limb during steps with head turns, accounting for footpath deviations first away from and then towards the paretic side. However, we found no significant relation between abnormal dissociation and increased footpath deviations in the stroke subjects.

Clinical implications

The findings from this study provide a clinically relevant assessment of the parameters most affected following a CVA, with respect to the coordination of gait and posture with head turns. Physiotherapists assessing their patients' safety during such a task should focus on the manner in which the movement is executed as well as the outcome on gait, especially in terms of footpath deviation and trunk movement. To further assess balance and stability, the walking and head turning task may be repeated in different environments or made more complex by adding a distracting mental task. Along with this study, future studies will help validate clinical scales such as the Advanced Mobility and Balance Scale that we have developed previously[16], to provide a quantitative clinical measure of balance during head turning.

The results from this study are not generalizable to patients with marked hemineglect, aphasia or visual disturbances or patients with cerebellar, brainstem or bilateral lesions. Undoubtedly, these types of deficits and lesions will impact on the control of posture and locomotion during head turns to a different extent.

Conclusion

This study provides a comparison of strategies used by stroke and healthy subjects when a head turn is performed during walking. In particular, the findings show that coordination of the head, trunk and pelvis with locomotion is disrupted during voluntary head turns in these patients. As well, this study contributes to the understanding of the impact of the head turn on forward locomotion and provides additional support for a feedforward control of head position during locomotion.

Acknowledgments

We are grateful for the assistance of E. Dannenbaum, R. Duprat, L. Galiana, N. Heron, E. Johnstone, A. Lamontagne and C. Paquette for this project. We also thank the volunteer office, the physiotherapists of the Jewish Rehabilitation Hospital and the patients who participated in this study. This project was financially supported by the Fonds de la recherche en santé du Québec (FRSQ), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Réseau provincial de recherche en adaptation-réadaptation (REPAR), the JRH Foundation, and the Faculty of Graduate Studies and Research of McGill University.

Figure legends

Figure 1.

Marker setup and coordinate frames of reference (global and local) used in the study's protocol.

Figure 2.

Illustration of footpath variables (A) Left and right 2nd toe trajectories represented by solid (—) and dashed line (---) respectively. Dark and light shaded zones represent surface area covered by the left and right foot respectively, over one right gait cycle delimited by solid long horizontal lines (——). Solid short horizontal bars (—) in light gray area represent divisions of gait cycle into 10 equally spaced intervals. (B) lateral position path over 2 gait cycles; (C) head turn deviation path over 2 gait cycles; (D) Calculation of Symmetry Index.

Figure 3.

A. Head angular displacement (thin line) and velocity traces (bold line) for one right hemiparetic subject and one healthy subject executing head turns in different directions. B. Comparison of head angular displacement and velocities (displayed as mean ± SD) between group (stroke n=10 and healthy n=5) and movement direction (up versus down versus right (ipsi for stroke group) versus left (contra for stroke group)).

ipsi= horizontal head turn towards the paretic side; contra= horizontal head turn away from the paretic side

↑ = onset of arrow signal; ⋮ = onset of head movement; *p<0.05, **p<0.01.

Figure 4.

Group means (±1 SE) of head and trunk excursions during the gait cycle of arrow presentation for stroke (white square) and healthy (black square) subjects executing horizontal, vertical and no head movements. *p<0.05; **p<0.01

Figure 5.

Coordination patterns between head and trunk (5A) and pelvis and trunk (5B) during head turning trials for one healthy subject (uppermost graph), one higher functional level stroke patient (middle graph), and one lower functional level stroke patient (lowermost graph). Stance and swing phases are represented by dashed (---) and solid (—) lines respectively. 5A. Two gait cycles (during and following arrow onset) are presented for each head turn direction. "O" with a letter in the middle indicates the beginning of the first gait cycle and the direction of the head turn (R=right; L=left; U=up; D=down). An "X" indicates the end of the second gait cycle. 5B. One gait cycle (during arrow onset) is presented for each head turn direction. The beginning of the gait cycle in indicated by an O with a letter in the middle (R,L,U,D) and the end is indicated by an X.

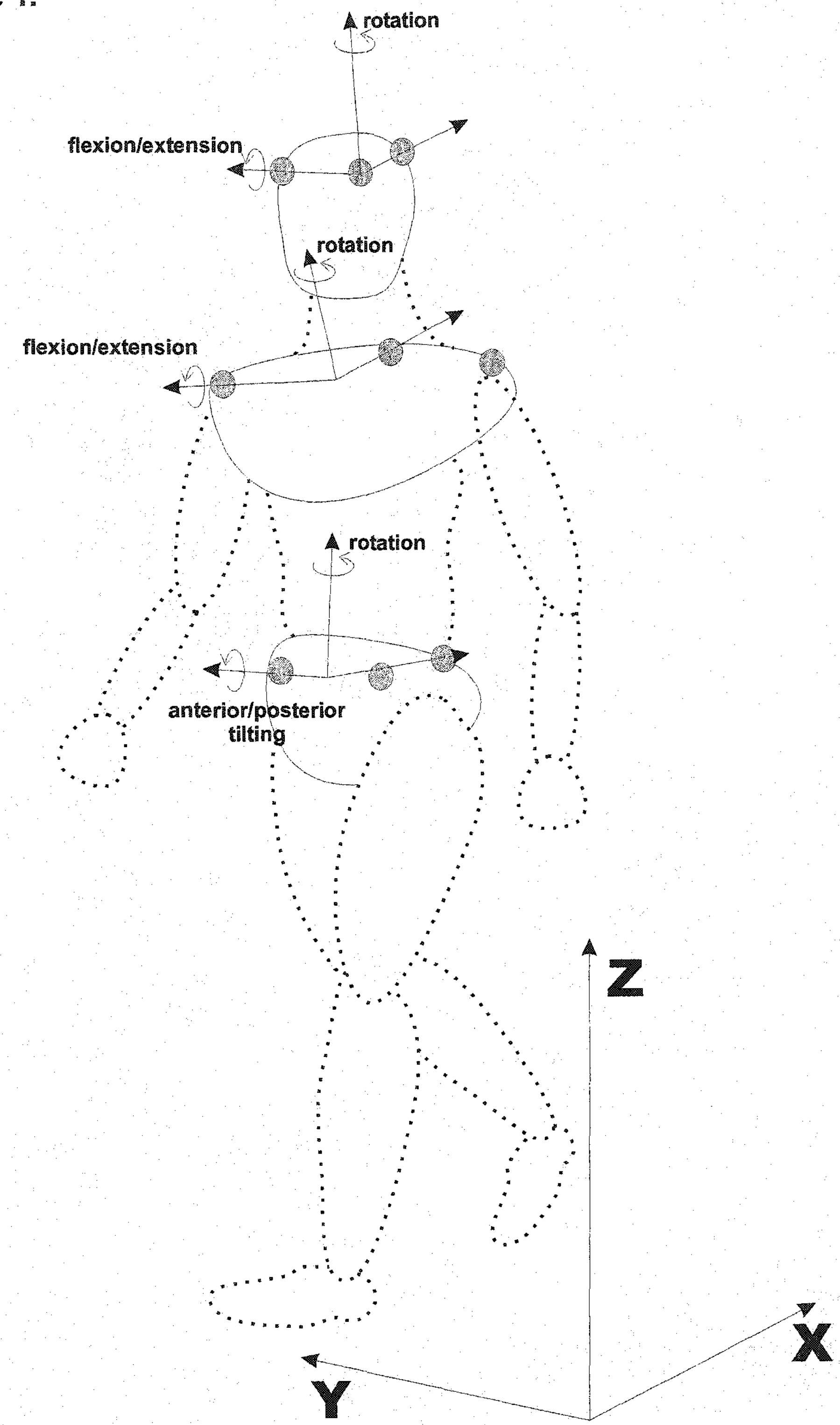
Figure 6.

A. Healthy, right hemiparetic and left hemiparetic group means of lateral foot position paths (solid line) +/- 1 SE (shaded area) over two gait cycles for trials with no head turns. B. Mean comparisons of head turn deviation paths for vertical versus horizontal head turns for stroke (white square) and healthy subjects (black square); $^*p<0.01$.

Figure 7.

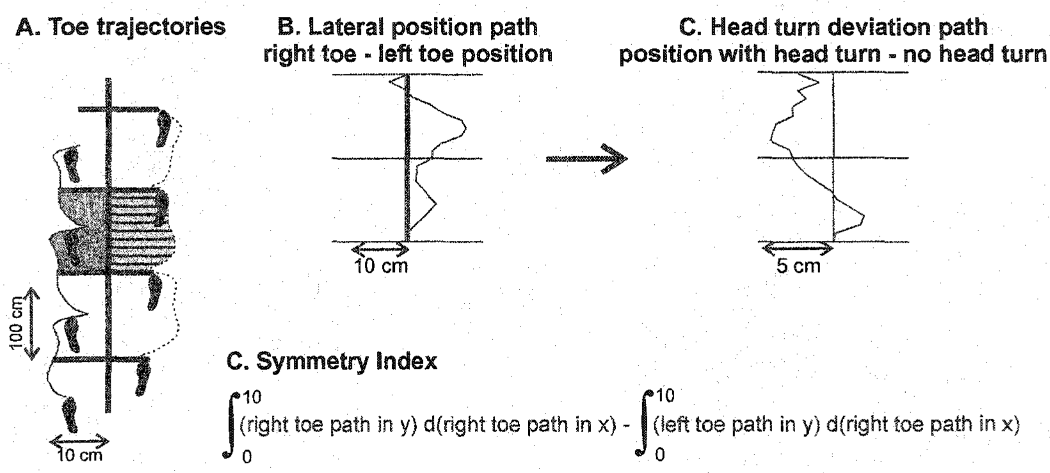
Mean Symmetry Indices in healthy and stroke subjects for steps during and after arrow presentation with right and left head turns. $^*p<0.05$

Figure 1.



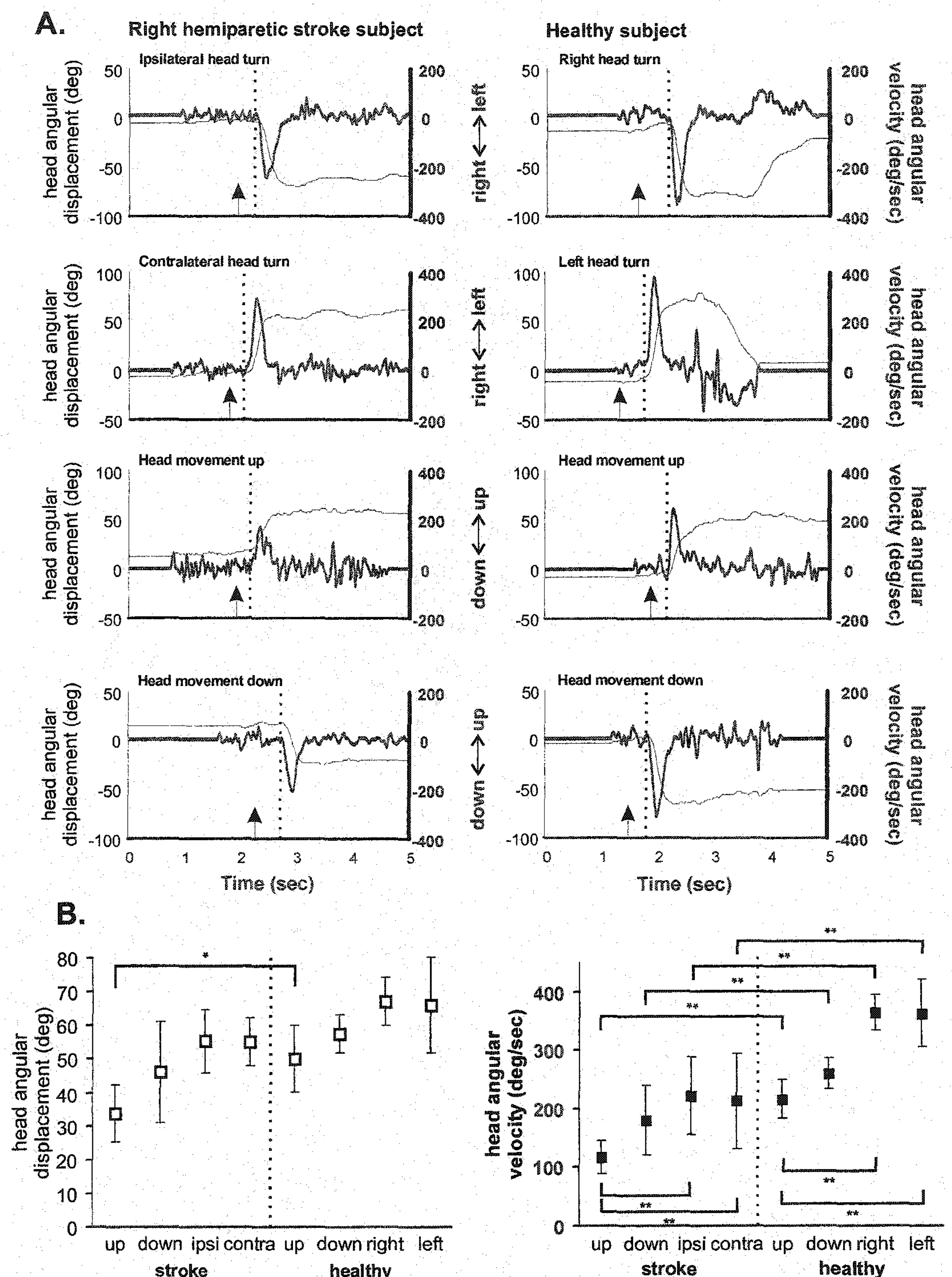
rotation
flexion/extension
rotation
flexion/extension
rotation
anterior/posterior
tilting
Z
X
Y

Figure 2.



$$\int_0^{10} (\text{right toe path in y})\, d(\text{right toe path in x}) - \int_0^{10} (\text{left toe path in y})\, d(\text{right toe path in x})$$

Figure 3.



A.
Right hemiparetic stroke subject
Healthy subject
Ipsilateral head turn
Right head turn
Contralateral head turn
Left head turn
Head movement up
Head movement up
Head movement down
Head movement down
head angular displacement (deg)
head angular velocity (deg/sec)
right ⟷ left
down ⟷ up
Time (sec)
B.
head angular displacement (deg)
head angular velocity (deg/sec)
up down ipsi contra up down right left
stroke
healthy

Figure 4.

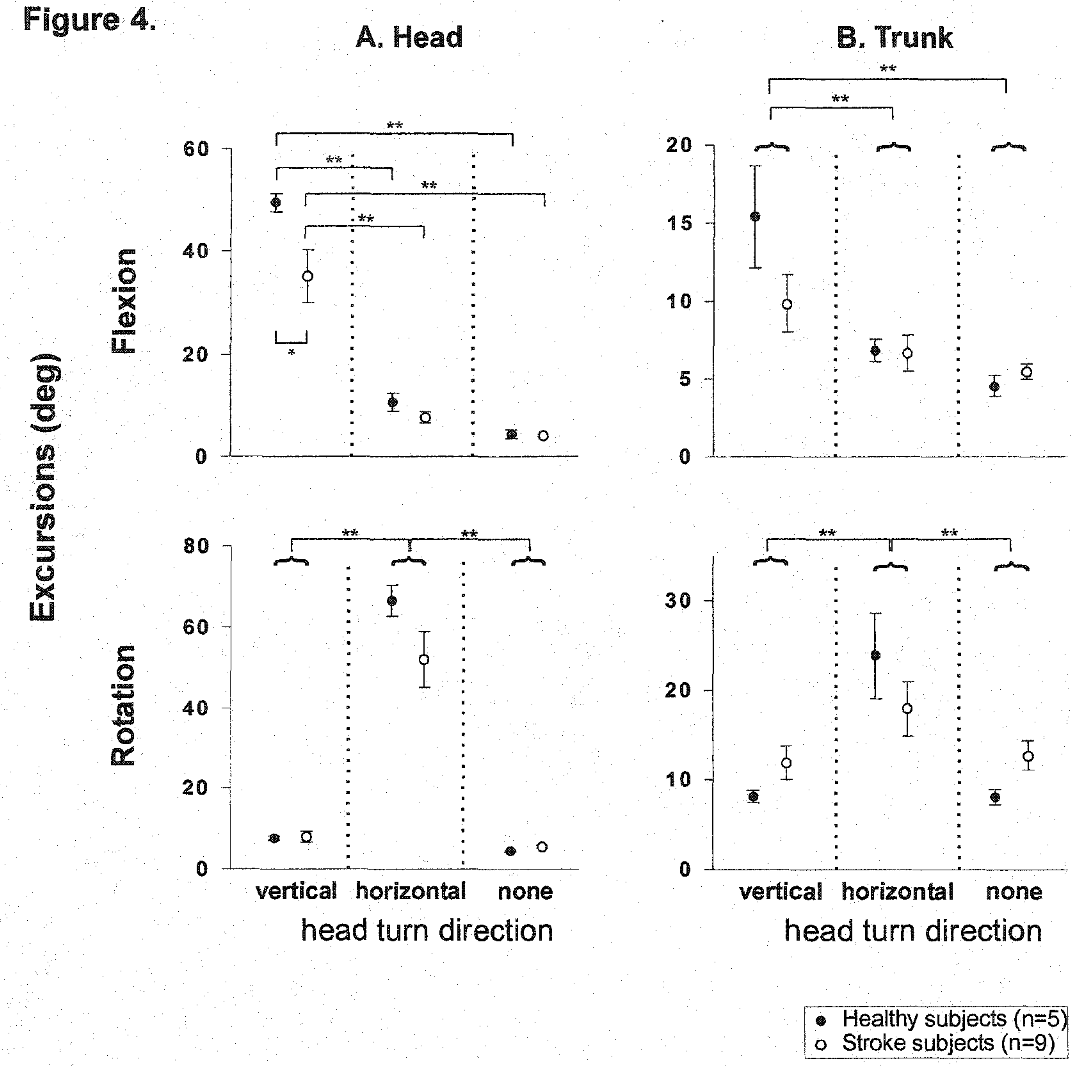

A. Head
B. Trunk
Excursions (deg)
Flexion
Rotation
60
40
20
0
80
60
40
20
0
20
15
10
5
0
30
20
10
0
**
*
vertical
horizontal
none
head turn direction
vertical
horizontal
none
head turn direction
Healthy subjects (n=5)
Stroke subjects (n=9)

Figure 5.

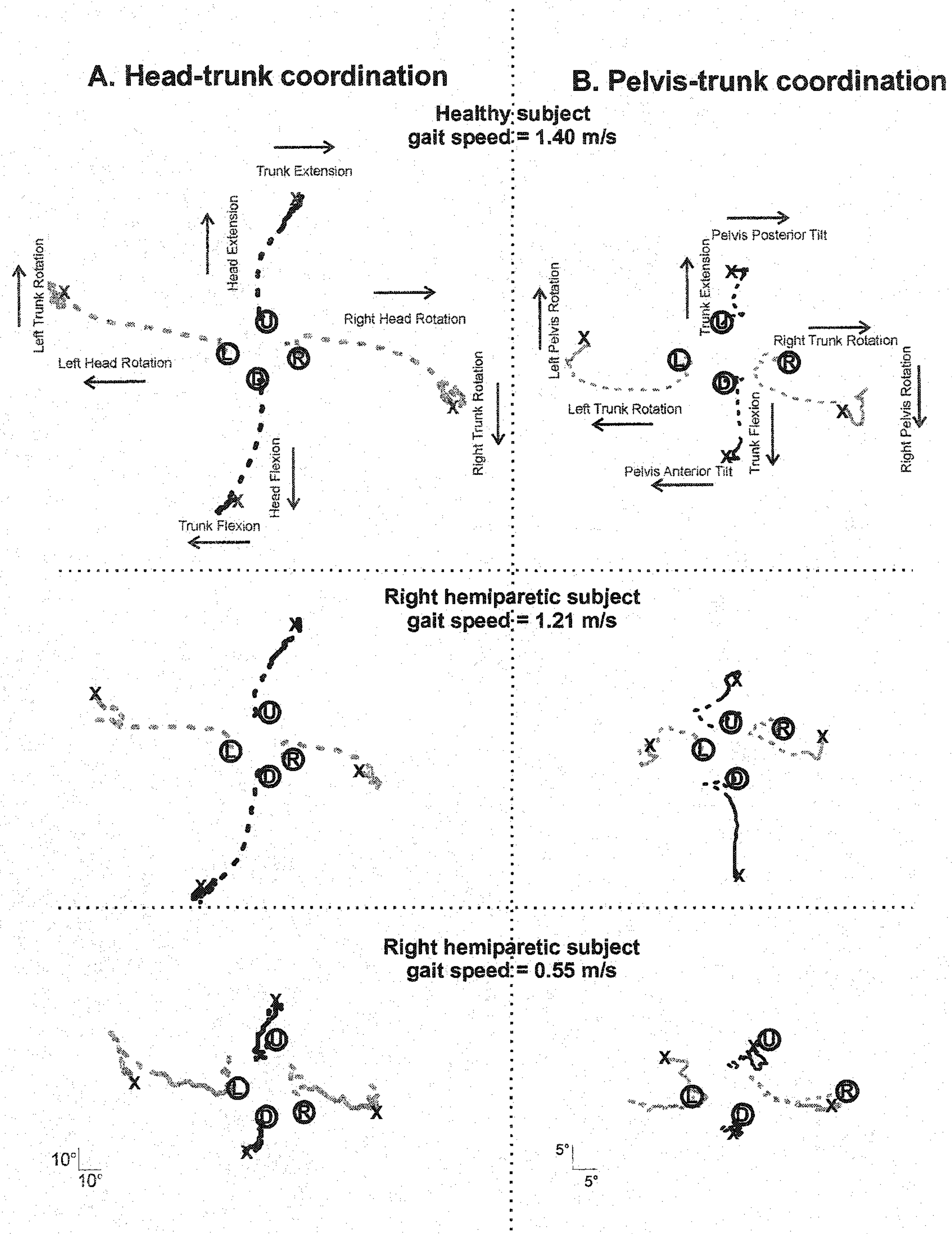

A. Head-trunk coordination
B. Pelvis-trunk coordination
Healthy subject
gait speed = 1.40 m/s
Trunk Extension
Head Extension
Left Trunk Rotation
Right Head Rotation
Left Head Rotation
Right Trunk Rotation
Head Flexion
Trunk Flexion
Pelvis Posterior Tilt
Trunk Extension
Left Pelvis Rotation
Right Trunk Rotation
Left Trunk Rotation
Trunk Flexion
Right Pelvis Rotation
Pelvis Anterior Tilt
Right hemiparetic subject
gait speed = 1.21 m/s
Right hemiparetic subject
gait speed = 0.55 m/s
10°
10°
5°
5°

Figure 6.

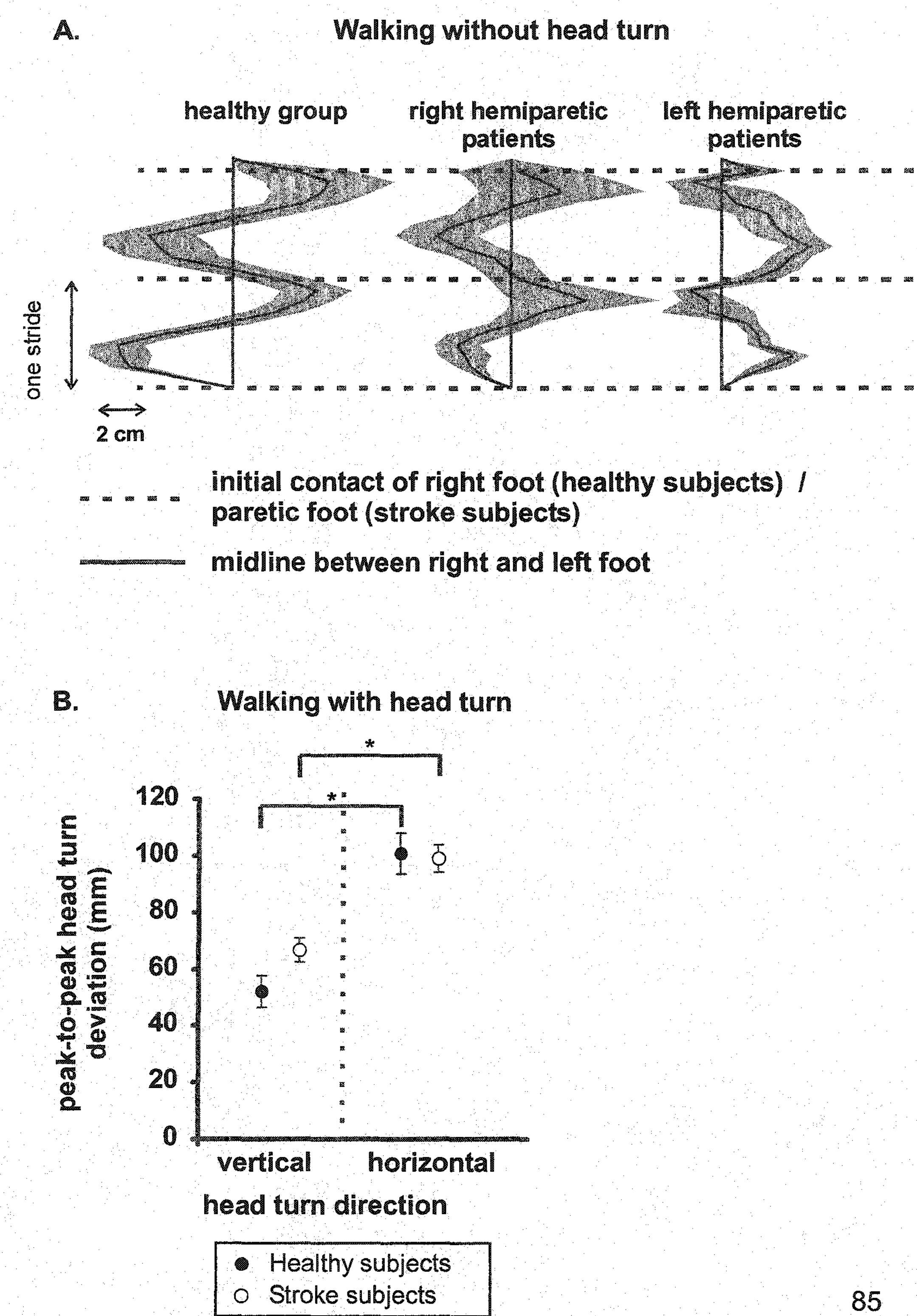
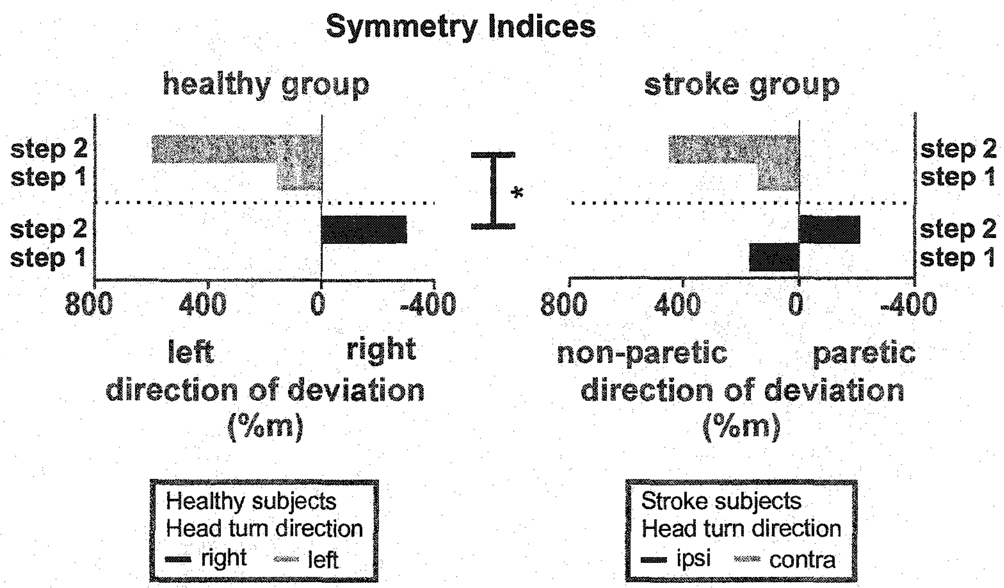

A.
Walking without head turn
healthy group
right hemiparetic patients
left hemiparetic patients
one stride
2 cm
initial contact of right foot (healthy subjects) / paretic foot (stroke subjects)
midline between right and left foot
B.
Walking with head turn
*
**
peak-to-peak head turn deviation (mm)
120
100
80
60
40
20
0
vertical
horizontal
head turn direction
Healthy subjects
Stroke subjects

Figure 7.



Symmetry Indices
healthy group
stroke group
step 2
step 1
step 2
step 1
*
step 2
step 1
step 2
step 1
800
400
0
-400
800
400
0
-400
left
right
direction of deviation
(%m)
non-paretic
paretic
direction of deviation
(%m)
Healthy subjects
Head turn direction
right
left
Stroke subjects
Head turn direction
ipsi
contra

Tables

Table 1. Subject Characteristics

Stroke Patients (n=10)		Gender	Age (Years)	Affected Side	Time since stroke (days)	Overground gait speed (m/s)	Chedoke Postural Control (/7)	Chedoke Leg (/7)	Berg (/56)
	1	M	69	R	94	0.49	5	4	50
	2	M	65	L	49	0.56	6	3	50
	3	M	65	R	212	1.21	6	6	53
	4	M	57	R	80	0.94	6	6	53
	5	F	56	L	61	0.40	5	6	50
	6	M	80	R	84	1.05	6	6	47
	7	M	79	R	62	0.55	5	6	44
	8	F	75	L	167	0.12	5	3	36
	9	M	61	L	107	0.12	5	3	38
	10	M	54	L	301	0.26	5	5	36
	mean	8 M / 2 F	66	5 R / 5 L	122	0.83	5.4	4.8	45.7
	SD		9.5		81	0.34	0.5	1.4	6.8
Healthy Subjects (n=5)	mean	3 M / 2 F	67			1.25			
	SD		9.3			0.19			

Chedoke=Chedoke-McMaster Stroke Assessment[17]
Berg=Berg Balance Scale[20]

Table 2. Head-Trunk and Pelvis-Trunk Excursion Ratios

		Head on Trunk ER (mean (±1 SE))		Pelvis on Trunk ER (mean (± 1 SE))	
Head Movement	Group	flexion	rotation	flexion	rotation
no head turn	stroke (n=9)	0.8 (0.2)	0.5 (0.1)	1.3 (0.5)	1.1 (0.6)
	healthy (n=5)	0.9 (0.3)	0.6 (0.2)	1.2 (0.2)	1.8 (1.0)
vertical	stroke	3.8 (1.1)	0.7 (0.3)	0.7 (0.3)	0.9 (0.3)
	healthy	3.9 (1.9)	1.0 (0.3)	0.5 (0.2)	1.7 (0.8)
horizontal	stroke	1.2 (0.3)	3.2 (1.0)	0.9 (0.3)	0.8 (0.3)
	healthy	1.7 (0.8)	3.5 (2.0)	0.8 (0.2)	0.7 (0.3)

ER=Excursion Ratio, SE=standard error

References

[1] Massion J. Movement, posture and equilibrium: interaction and coordination. Prog Neurobiol 1992;38:35-56.

[2] Horak FB, Macpherson JM. Postural orientation and equilibrium. In: Rowell LB, Sheperd JT, editors. Handbook of Physiology, section 12, Exercise: Regulation and Integration of Multiple Systems. New York: Oxford University Press, 1996:255-292.

[3] Nashner LM, Forssberg H. Phase-dependent organization of postural adjustments associated with arm movements while walking. J Neurophysiol 1986;55:1382-94.

[4] Hirschfeld H, Forssberg H. Phase-dependent modulations of anticipatory postural activity during human locomotion. J Neurophysiol 1991;66:12-9.

[5] Grasso R, Glasauer S, Takei Y, Berthoz A. The predictive brain: anticipatory control of head direction for the steering of locomotion. Neuroreport 1996;7:1170-4.

[6] Patla AE, Adkin A, Ballard T. Online steering: coordination and control of body center of mass, head and body reorientation. Exp Brain Res 1999;129:629-34.

[7] Shumway-Cook A, Baldwin M, Polissar N, Gruber W. Predicting the probability for falls in community-dwelling older adults. Phys Ther 1997;77:812-819.

[8] Vallis LA, Patla AE, Adkin AL. Control of steering in the presence of unexpected head yaw movements. Influence on sequencing of subtasks. Exp Brain Res 2001;138:128-34.

[9] Grasso R, Prevost P, Ivanenko YP, Berthoz A. Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. Neurosci Lett 1998;253:115-8.

[10] Evarts EV. Motor cortex reflexes associated with learned movement. Science 1973;179:501-3.

[11] Paquette C, Lamontagne A, Kairy D, Paquet N, Fung J. Fast head turns modify ground reaction forces during walking. Soc Neurosci Abstr 2000;26:459.

[12] Horak FB, Esselman P, Anderson ME, Lynch MK. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. J Neurol Neurosurg Psychiatry 1984;47:1020-8.

[13] Bennis N, Roby-Brami A, Dufosse M, Bussel B. Anticipatory responses to a self-applied load in normal subjects and hemiparetic patients. J Physiol Paris 1996;90:27-42.

[14] Badke MB, Duncan PW. Patterns of rapid motor responses during postural adjustments when standing in healthy subjects and hemiplegic patients. Phys Ther 1983;63:13-20.

[15] Rogers MW, Hedman LD, Pai YC. Kinetic analysis of dynamic transitions in stance support accompanying voluntary leg flexion

movements in hemiparetic adults. Arch Phys Med Rehabil 1993;74:19-25.

[16] Kairy D, Paquet N, Fung J. A postural adaptation test for stroke patients. Clin Rehabil (submitted).

[17] Gowland C, VanHullenaar S, Torresin W, Moreland J, Vanspall B, Barrecca S, et al. Chedoke-McMaster Stroke Assessment: Development, Validation and Administration Manual. Hamilton: Chedoke-McMaster Hospitals and McMaster University, 1995.

[18] Keith RA, Granger CV, Hamilton BB, Sherwin FS. The Functional Independence Measure: a new tool for rehabilitation. In: Eisenberg MG, Grzesiak RC, editors. Advances in Clinical Rehabilitation. New York: Springer, 1987:6-18.

[19] Winter D. The Biomechanics and Motor Control of Human Movement. 2nd ed. New York: John Wiley & Sons, 1990.

[20] Berg KO, Wood-Dauphinee SL, Williams JI. The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. Scand J Rehabil Med 1995;27: 27-36.

[21] Garland SJ, Stevenson TJ, Ivanova T. Postural responses to unilateral arm perturbation in young, elderly, and hemiplegic subjects. Arch Phys Med Rehabil 1997;78:1072-7.

[22] Hollands MA, Sorensen KL, Patla AE. Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. Exp Brain Res 2001;140:223-33.

[23] Pozzo T, Levik Y, Berthoz A. Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans. Exp Brain Res 1995;106:327-38.

[24] Bloomberg JJ, Peters BT, Smith SL, Huebner WP, Reschke MF. Locomotor head-trunk coordination strategies following space flight. J Vestib Res 1997;7:161-77.

[25] Pozzo T, Berthoz A, Lefort L. Head stabilization during various locomotor tasks in humans. I. Normal subjects. Exp Brain Res 1990;82:97-106.

[26] Keshner EA, Hain TC, Chen KJ. Predicting control mechanisms for human head stabilization by altering the passive mechanics. J Vestib Res 1999;9:423-34.

CHAPTER 4

CONCLUSION

Summary

Developing valid and reliable clinical measures of postural control for stroke patients is essential not only for the purpose of measurement but also in targeting treatments to maximize recovery. Measures that provide information beyond the ability to perform a task, such as quality of performance, allow clinicians to individualize treatment strategies more effectively. In this study, we found that the Advanced Mobility and Balance Scale had excellent interrater reliability and good discriminative validity. In order to increase the discriminative capacity of the AMBS, we conducted a kinematic analysis of one of the tasks from the scale, *head turning during walking*. Results from the kinematic analysis provide important information about normal postural adaptations and offer preliminary insight into their disruption and/or reorganization following a CVA. We now know that trunk and pelvis control as well as footpath during head turning are important parameters that may not be appropriately controlled in a stroke patient.

Future directions

Our findings provide evidence that future clinical and laboratory studies on balance during locomotion should include measures of head, trunk and pelvis control. In addition, studies of muscle activity in the neck, trunk and pelvis are needed to confirm and expand our knowledge on segment coordination during locomotion.

Using the results from these studies, the qualitative scoring of the AMBS head turning task may now be improved to reflect our knowledge on normal and abnormal postural adaptation strategies. For example, initial scoring for that item was limited to observing fluidity of limb movements. It is now evident that head-trunk coordination should also be observed. On the other hand, the small pelvis excursions are harder to identify clinically. Therefore, while the current score should be maintained, an additional subscore could be added to take into account trunk movements. Moreover, deviation of footpath, which may be increased or reversed in stroke patients, could easily be measured in a clinical setting using a straight-line marking on the floor. Taking these new findings into account, an example of scoring for the *head turning during walking* task is provided below:

0. Unable to complete the task <u>or</u> requires physical assistance
1. Unable to maintain the trunk stable for the step during and following head movement <u>or</u> subject steers in the opposite direction to the head turn
2. Maintains the trunk stable for some period during the head turn but trunk movement is not in the same direction as head movement
3. Maintains the trunk stable during the head movement. When trunk movement is present, it is in the same direction as the head movement.

It is clear that a kinematic analysis needs to be conducted for the other tasks on the AMBS, namely standing and turning the head, and standing and walking on a slope, in order to better identify normal postural adjustments and characterize the deficits that occur post stroke. In fact, the normal and abnormal strategies used during a task that is part of an ordinal scale such as the AMBS need to be identified in order to ensure that the scale paints a true picture of the patient's abilities. This will in turn provide clinicians with the necessary tools for planning appropriate rehabilitation interventions.

Finally, rehabilitation strategies aimed at improving balance during walking in stroke patients should include a focus on trunk and pelvis control during head movements. In addition, their effectiveness must be demonstrated in clinical trials. Identifying the most effective rehabilitation strategy may reduce the risk of falling for these patients and thus not only prevent subsequent hospitalizations and the associated costs for the health care system, but ultimately improve the patient's quality of life.

REFERENCE LIST

Arsenault, A.B., Winter, D.A. and Marteniuk, R.G. Treadmill versus walkway locomotion in humans: an EMG study. Ergonomics. 29: 665-676, 1986.

Badke, M.B., Di Fabio, R.P., Leonard, E., Margolis, M. and Franke, T. Reliability of a functional mobility assessment tool with application to neurologically impaired patients: a preliminary report. Physiother. Can. 45: 15-20, 1993.

Badke, M.B. and Duncan, P.W. Patterns of rapid motor responses during postural adjustments when standing in healthy subjects and hemiplegic patients. Phys. Ther. 63: 13-20, 1983.

Benaim, C., Perennou, D.A., Villy, J., Rousseaux, M. and Pelissier, J.Y. Validation of a standardized assessment of postural control in stroke patients: the Postural Assessment Scale for Stroke Patients (PASS). Stroke. 30: 1862-1868, 1999.

Bennis, N., Roby-Brami, A., Dufosse, M. and Bussel, B. Anticipatory responses to a self-applied load in normal subjects and hemiparetic patients. J. Physiol. Paris. 90: 27-42, 1996.

Berg, K.O., Maki, B.E., Williams, J.I., Holliday, P.J. and Wood-Dauphinee, S.L. Clinical and laboratory measures of postural balance in an elderly population. Arch. Phys. Med. Rehabil. 73: 1073-1080, 1992a.

Berg, K.O., Wood-Dauphinee, S.L., Williams, J.I. and Maki, B. Measuring balance in the elderly: validation of an instrument. Can. J. Public Health. 83: S7-11, 1992b.

Berg, K.O., Wood-Dauphinee, S.L. and Williams, J.I. The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. Scand. J. Rehabil. Med. 27: 27-36, 1995.

Bloomberg, J.J., Peters, B.T., Smith, S.L., Huebner, W.P. and Reschke, M.F. Locomotor head-trunk coordination strategies following space flight. J. Vestib. Res. 7: 161-177., 1997.

Bohannon, R. Gait performance of hemiparetic stroke patients: selected variables. Arch. Phys. Med. Rehabil. 68: 777-781, 1987.

Bohannon, R.W., Walsh, S. and Joseph, M.C. Ordinal and timed balance measurements: reliability and validity in patients with stroke. Clin. Rehabil. 7: 9-13, 1993.

Bonita, R., Solomon, N. and Broad, J.B. Prevalence of stroke and stroke-related disability. Estimates from the Auckland stroke studies. Stroke. 28: 1898-1902, 1997.

Bouisset, S. and Zattara, M. Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J. Biomech. 20: 735-742, 1987.

Cole, B., Finch, E., Gowland, C. and Mayo, N. Physical rehabilitation outcome measures. Toronto: Canadian Physiotherapy Association, 1994.

Cordo, P.J. and Nashner, L.M. Properties of postural adjustments associated with rapid arm movements. J. Neurophysiol. 47: 287-302, 1982.

Dettmann, M.A., Linder, M.T. and Sepic, S.B. Relationships among walking performance, postural stability, and functional assessments of the hemiplegic patient. Am. J. Phys. Med. 66: 77-90, 1987.

Duncan, P., Weiner, D., Chandler, J. and Studenski, S. Functional Reach: a new clinical measure of balance. J. Gerontol. 45: M192-M197, 1990.

Evarts, E.V. Motor cortex reflexes associated with learned movement. Science. 179: 501-503, 1973.

Forster, A. and Young, J. Incidence and consequences of falls due to stroke: a systematic inquiry. B.M.J. 311: 83-86, 1995.

Frank, J.S. and Earl, M. Coordination of posture and movement. Phys. Ther. 70: 855-863, 1990.

Garland, S.J., Stevenson, T.J. and Ivanova, T. Postural responses to unilateral arm perturbation in young, elderly, and hemiplegic subjects. Arch. Phys. Med. Rehabil. 78: 1072-1077, 1997.

Ghez, C. Posture. In: Principles of Neural Science. Edited by Kandel, E., Schwartz, J. and Jessel, T. Norwalk: Appleton and Lange, 1991, pp.596-607.

Gowland, C., VanHullenaar, S., Torresin, W., Moreland, J., Vanspall, B., Barrecca, S., Ward, M., Huijbregts, M., Stratford, P. and Barclay-Goddard, R. Chedoke-McMaster Stroke Assessment: Development, Validation and Administration Manual. Hamilton: Chedoke-McMaster Hospitals and McMaster University, 1995.

Granger, C.V., Hamilton, B.B. and Gresham, G.E. The stroke rehabilitation outcome study - Part I: General description. Arch. Phys. Med. Rehabil. 69: 506-509, 1988.

Grasso, R., Glasauer, S., Takei, Y. and Berthoz, A. The predictive brain: anticipatory control of head direction for the steering of locomotion. Neuroreport. 7: 1170-1174, 1996.

Grasso, R., Prevost, P., Ivanenko, Y.P. and Berthoz, A. Eye-head coordination for the steering of locomotion in humans: an anticipatory synergy. Neurosci. Lett. 253: 115-118, 1998.

Gurfinkel, V.S., Popov, K.E., Smetanin, B.N. and Shilkov, V.Y. Body scheme in the control of postural activity. In: Stance and Motion: Facts and Theories. Edited by Gurfinkel, V.S., Ioffe, M.E., Massion, J. and Roll, J.P. New York: Plenum Press, 1988, pp.185-193.

Hankey, G. Stroke: how large a public health problem, and how can the neurologist help? Arch. Neurol. 56: 748-754, 1999.

Harburn, K.L., Hill, K.M., Kramer, J.F., Noh, S., Vandervoort, A.A. and Teasell, R. Clinical applicability and test-retest reliability of an external perturbation test of balance in stroke subjects. Arch. Phys. Med. Rehabil. 76: 317-323, 1995.

Hedman, L.D., Rogers, M.W., Pai, Y.C. and Hanke, T.A. Electromyographic analysis of postural responses during standing leg flexion in adults with hemiparesis. Electroencephalogr. Clin. Neurophysiol. 105: 149-155, 1997.

Heart and Stroke Foundation of Canada. Changing Face of Heart Disease and Stroke in Canada. 1999.

Hirschfeld, H. and Forssberg, H. Phase-dependent modulations of anticipatory postural activity during human locomotion. J. Neurophysiol. 66: 12-19, 1991.

Hodges, P., Cresswell, A. and Thorstensson, A. Preparatory trunk motion accompanies rapid upper limb movement. Exp. Brain Res. 124: 69-79, 1999.

Hollands, M.A., Sorensen, K.L. and Patla, A.E. Effects of head immobilization on the coordination and control of head and body reorientation and translation during steering. Exp. Brain Res. 140: 223-233, 2001.

Horak, F.B., Esselman, P., Anderson, M.E. and Lynch, M.K. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. J. Neurol. Neurosurg. Psychiatry. 47: 1020-1028, 1984.

Horak, F.B. and Macpherson, J.M. Postural orientation and equilibrium. In: Handbook of Physiology, Section 12, Exercise: Regulation and Integration of Multiple Systems. Edited by Rowell, L.B. and Sheperd, J.T. New York: Oxford University Press, 1996, pp.255-292.

Jorgensen, H., Nakayama, H., Raaschou, H., Vive-Larsen, J., Stoier, M. and Olsen, T. Outcome and time course of recovery in stroke. Part I: Outcome. The Copenhagen Stroke Study. Arch. Phys. Med. Rehabil. 76: 399-405, 1995.

Jorgensen, H., Nakayama, H., Raaschou, H., Vive-Larsen, J., Stoier, M. and Olsen, T. Outcome and time course of recovery in stroke. Part II: Time course of recovery. The Copenhagen Study. Arch. Phys. Med. Rehabil. 76: 406-411, 1995.

Kairy, D., Paquet, N. and Fung, J. Development of a postural adaptation test battery in stroke. Physiother. Can. 52: S98, 2000.

Kairy, D., Paquet, N. and Fung, J. A postural adaptation test for stroke patients. Clin Rehabil (submitted).

Keith, R.A., Granger, C.V., Hamilton, B.B. and Sherwin, F.S. The Functional Independence Measure: a new tool for rehabilitation. In: Advances in Clinical Rehabilitation. Edited by Eisenberg, M.G. and Grzesiak, R.C. New York: Springer, 1987, pp.6-18.

Keshner, E.A., Hain, T.C. and Chen, K.J. Predicting control mechanisms for human head stabilization by altering the passive mechanics. J. Vestib. Res. 9: 423-434., 1999.

King, M. and Tinetti, M. Falls in community-dwelling older persons. J. Am. Geriatr. Soc. 43: 1146-1154, 1995.

King, M.B., Judge, J.O., Whipple, R. and Wolfson, L. Reliability and responsiveness of two physical performance measures examined in the context of a functional training intervention. Phys. Ther. 80: 8-16, 2000.

Layne, C.S. and Abraham, L.D. Interactions between automatic postural adjustments and anticipatory postural patterns accompanying voluntary movement. Int. J. Neurosci. 61: 241-254, 1991.

Leroux, A., Fung, J. and Barbeau, H. Postural adaptation to walking on inclined surfaces: I. Normal strategies. Gait Posture: in press, 2002.

Leroux, A., Fung, J. and Barbeau, H. Adaptation of the walking pattern to uphill walking in normal and spinal-cord injured subjects. Exp. Brain Res. 126: 359-368, 1999.

Liston, R.A. and Brouwer, B.J. Reliability and validity of measures obtained from stroke patients using the Balance Master. Arch. Phys. Med. Rehabil. 77: 425-430, 1996.

Massion, J. Movement, posture and equilibrium: interaction and coordination. Prog. Neurobiol. 38: 35-56, 1992.

Mayo, N. Hospitalization and case-fatality rates for stroke in Canada from 1982 through 1991. The Canadian Collaborative study group of stroke hospitalizations. Stroke. 27: 1215-1220, 1996.

Mayo, N.E., Wood-Dauphinee, S., Ahmed, S., Gordon, C., Higgins, J., McEwen, S. and Salbach, N. Disablement following stroke. Disabil. Rehabil. 21: 258-268, 1999.

McFadyen, B.J. and Carnahan, H. Anticipatory locomotor adjustments for accommodating versus avoiding level changes in humans. Exp. Brain Res. 114: 500-506, 1997.

Means, K.M., Rodell, D.E. and O'Sullivan, P.S. Use of an obstacle course to assess balance and mobility in the elderly. A validation study. Am. J. Phys. Med. Rehabil. 75: 88-95, 1996.

Means, K.M., Rodell, D.E., O'Sullivan, P.S. and Winger, R.M. Comparison of a functional obstacle course with an index of clinical gait and balance and postural sway. J. Gerontol. A. Biol. Sci. Med. Sci. 53: M331-335, 1998.

Merfeld, D.M., Young, L.R., Oman, C.M. and Shelhamer, M.J. A multidimensional model of the effect of gravity on the spatial orientation of the monkey. J. Vestib. Res. 3: 141-161, 1993.

Nashner, L.M. and Forssberg, H. Phase-dependent organization of postural adjustments associated with arm movements while walking. J. Neurophysiol. 55: 1382-1394, 1986.

Paquet, N., Kairy, D. and Fung, J. Changes in ground reaction force do not precede fast head turns in standing humans. Soc. Neurosci. Abstr. 25: 108, 1999.

Paquette, C., Lamontagne, A., Kairy, D., Paquet, N. and Fung, J. Fast head turns modify ground reaction forces during walking. Soc. Neurosci. Abstr 26: 459, 2000.

Patla, A. Effects of walking on various inclines on EMG patterns of lower limb muscles in humans. Human Movement Science. 5: 345-357, 1986.

Patla, A.E., Adkin, A. and Ballard, T. Online steering: coordination and control of body center of mass, head and body reorientation. Exp. Brain Res. 129: 629-634, 1999.

Podsiadlo, D. and Richardson, S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. J. Am. Geriatr. Soc. 39: 142-148, 1991.

Pozzo, T., Berthoz, A. and Lefort, L. Head stabilization during various locomotor tasks in humans. I. Normal subjects. Exp. Brain Res. 82: 97-106., 1990.

Pozzo, T., Levik, Y. and Berthoz, A. Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans. Exp. Brain Res. 106: 327-338., 1995.

Reuben, D.B. and Siu, A.L. An objective measure of physical function of elderly outpatients. The Physical Performance Test. J. Am. Geriatr. Soc. 38: 1105-1112, 1990.

Rizzo, J., Friedkin, R., Williams, C., Nabors, J., Acampora, D. and Tinetti, M. Health care utilization and costs in a medicare population by fall status. Medical Care. 36: 1174-1188, 1998.

Rogers, M.W., Hedman, L.D. and Pai, Y.C. Kinetic analysis of dynamic transitions in stance support accompanying voluntary leg flexion movements in hemiparetic adults. Arch. Phys. Med. Rehabil. 74: 19-25, 1993.

Rogers, M.W. and Pai, Y.C. Dynamic transitions in stance support accompanying leg flexion movements in man. Exp. Brain Res. 81: 398-402, 1990.

Shumway-Cook, A., Baldwin, M., Polissar, N. and Gruber, W. Predicting the probability for falls in community-dwelling older adults. Phys. Ther. 77: 812-819, 1997.

Shumway-Cook, A. and Woollacott, M. Motor Control - Theory and Practical Applications. Baltimore: Williams and Wilkins, 1995.

Stineman, M., Maislin, M., Fiedler, R. and Granger, C. A prediction model for functional recovery in stroke. Stroke. 28: 550-556, 1997.

Streiner, D. and Norman, G. Health Measurement Scales: a Practical Guide to their Development and Use. Oxford: Oxford University Press, 1995.

Sudlow, C.L. and Warlow, C.P. Comparable studies of the incidence of stroke and its pathological types: results from an international collaboration. International Stroke Incidence Collaboration. Stroke. 28: 491-499, 1997.

Tang, P.F., Moore, S. and Woollacott, M.H. Correlation between two clinical balance measures in older adults: functional mobility and sensory organization test. J. Gerontol. 53A: M140-M146, 1998.

Tang, P.F. and Woollacott, M.H. Phase-dependent modulation of proximal and distal postural responses to slips in young and older adults. J. Gerontol. A. Biol. Sci. Med. Sci. 54: M89-102, 1999.

Tennant, A., Geddes, J.M., Fear, J., Hillman, M. and Chamberlain, M.A. Outcome following stroke. Disabil. Rehabil. 19: 278-284, 1997.

Tinetti, M.E. and Williams, C.S. The effect of falls and fall injuries on functioning in community-dwelling older persons. J. Gerontol. A. Biol. Sci. Med. Sci. 53: M112-119, 1998.

Turnbull, G., Charteris, J. and Wall, J. Deficiencies in standing weight shifts by ambulant hemiplegic subjects. Arch. Phys. Med. Rehabil. 77: 356-362, 1996.

Vallis, L. and Patla, A. Voluntary head turn does not result in foot placement modification of gait. In: Control of Posture and Gait. Edited by Duysens, J., Smits-Engelsman, B. and Kingma, H., 2001, pp.494-498.

Vallis, L.A., Patla, A.E. and Adkin, A.L. Control of steering in the presence of unexpected head yaw movements. Influence on sequencing of subtasks. Exp. Brain Res. 138: 128-134., 2001.

Wade, D.T., Skilbeck, C.E. and Hewer, R.L. Predicting Barthel ADL score at 6 months after an acute stroke. Arch. Phys. Med. Rehabil. 64: 24-28, 1983.

Wee, J.Y., Bagg, S.D. and Palepu, A. The Berg balance scale as a predictor of length of stay and discharge destination in an acute stroke rehabilitation setting. Arch. Phys. Med. Rehabil. 80: 448-452, 1999.

Wernick-Robinson, M., Krebs, D.E. and Giorgetti, M.M. Functional reach: does it really measure dynamic balance? Arch. Phys. Med. Rehabil. 80: 262-269, 1999.

WHO. World Health Organization International Classification of Impairments, Disabilities and Handicaps: a Manual of Classification Relating to the Consequences of Disease. 1980.

WHO. International Classification of Functioning and Disability. Geneva: World Health Organization, 1999.

Winter, D. The Biomechanics and Motor Control of Human Movement. New York: John Wiley & Sons, 1990.

Winter, D. The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological. Waterloo: University of Waterloo Press, 1991.

Wolfson, L.I., Whipple, R. and Amerman, P. Stressing the postural response: a quantitative method for testing balance. J. Am. Geriatr. Soc. 34: 845-850, 1986.