Contribution of Muscle Strength and Integration of Afferent Input to Postural Instability in Persons with Stroke

Daniel S. Marigold^{1,3}, Janice J. Eng^{1,2,3}, Craig D. Tokuno³, and Catherine A. Donnelly³

¹Graduate Program in Neuroscience, University of British Columbia

²Department of Physical Therapy, University of British Columbia

³Rehab Research Lab, G.F. Strong Rehab Centre, Vancouver, B.C., Canada

Abstract

Objectives—To determine the relationship of muscle strength to postural sway in persons with stroke under standing conditions in which vision and ankle proprioception were manipulated.

Methods—Forty persons with stroke and 40 healthy older adult controls were recruited from the community and underwent balance testing consisting of six conditions that manipulate vision and somatosensory information while standing. Postural sway was measured during each condition. In addition, lower extremity joint torques and cutaneous sensation from the plantar surface of the foot were assessed.

Results—Postural sway was increased with more challenging standing conditions (i.e. when multiple sensory systems were manipulated) to a greater extent with the group with stroke compared to controls. Muscle strength was only correlated to sway during the most challenging conditions. Furthermore, a greater number of persons with stroke fell during the balance testing compared to controls.

Conclusions—Impairments in re-weighting/integrating afferent information, in addition to muscle weakness appear to contribute to postural instability and falls in persons with stroke. These findings can be used by clinicians to design effective interventions for improving postural control following stroke.

Keywords

sway; cerebrovascular accident; muscle strength; sensory integration

INTRODUCTION

Stroke occurs most commonly after age 65 and is the leading cause of severe long-term disability.¹ Falling is a major concern among persons with stroke: Forster and Young² have reported the incidence of falls to be as high as 73% of persons with stroke falling within six months following hospital discharge. More recently, Hyndman et al.³ have reported 50% of

Please send all correspondence to the second author: Janice J. Eng, PhD, PT/OT, Professor, Department of Physical Therapy, 212-2177 Wesbrook Mall, University of BC, Vancouver, BC, Canada, V6T 1Z3, Phone: (604) 714-4105, FAX: (604) 714-4168, Janice.eng@ubc.ca.

persons with stroke living in the community experienced at least one fall over the course of a year with approximately 50% of those individuals falling repeatedly.

Falls occur as a result of the inability to recover from a loss of balance and postural stability plays a major role. Postural stability is defined as the ability to maintain the position of the body's centre of mass within specific boundaries of space or stability limits⁴ and can be quantified by the amount of body sway (i.e. postural sway).

Muscle weakness can be severe on the paretic side following stroke⁵, with slight weakness with the non-paretic muscles in comparison to healthy older adults.⁶ The effects on the muscles ipsilateral to the lesion (i.e. non-paretic side) likely result from the small percentage of cortical tracts that descend ipsilaterally.⁷ Given that muscle strength (i.e. knee extensors) has been shown to be an independent predictor of postural sway in healthy older adults during standing on an unstable surface,⁸ one might expect to find similar results with persons with stroke.

However, given that standing balance does not require maximal muscle activation, it is possible that the effects from impairments of the sensory systems following a stroke have a larger role than motor impairment during quiet standing. Three major sensory systems, the visual, vestibular, and somatosensory, contribute to postural stability. Each system cannot provide the central nervous system (CNS) a complete picture of body position and movement for the control of posture, but rather it is the integration of all three systems that enables us to maintain balance and prevent a fall. Injury to the CNS from stroke may disrupt normal neural processing centres responsible for the processing and integration of afferent input from these systems and contribute to the large number of falls in these individuals.

In stroke, postural stability is compromised (i.e. increased postural sway) when vision is removed (eyes closed) during standing compared to when vision is available.⁹ In addition, postural sway is correlated to ankle proprioception in stroke⁹ suggesting an important role of the somatosensory system in these individuals. Furthermore, vestibular processing may be impaired in stroke and could potentially affect postural sway.¹⁰

Although impairments in all three sensory systems may exist in persons with stroke, little is known about the ability to integrate afferent information in this population and its relationship to postural stability and falls. Recently, Bonan et al.¹¹ demonstrated greater postural sway during altered visual and ankle proprioception standing conditions in persons with stroke compared to healthy older adults.

Further insight into the mechanisms which contribute to the impaired postural stability and greater fall risk in persons with stroke is vital for developing effective rehabilitation programs to reduce the number of falls in these individuals. Therefore, the purpose of this study was to determine the relationship of muscle strength to postural sway in persons with stroke under standing conditions in which vision and ankle proprioception were manipulated.

METHODS

Participants

Forty older adults with hemiparesis due to stroke were recruited from the community. The level of disability of the persons with stroke was described by the American Heart Association Stroke Functional Classification (AHASFC). The AHASFC was attained from an interview with each subject and is based on level of independence of an individual where level I represents complete independence in basic and instrumental daily activities of living and level V represents complete dependence.¹² Participant characteristics are described in Table 1. The inclusion criteria for the persons with stroke were: (1) over 50 years of age, (2) first stroke, (3) at least one year post stroke, (4) able to stand independently for at least 5 minutes without an assistive device, and (5) able to follow two-step commands. Persons with neurological (e.g. Parkinson's disease) or severe musculoskeletal conditions (e.g. recent joint replacement surgery, amputations) in addition to their stroke were excluded from the study. A family physician confirmed the inclusion criteria and the diagnosis of stroke. Information regarding the type and location of the participant's stroke was collected through medical records and/or physician notes. Forty healthy older adults at least 50 years old and who had no known neurological or severe musculoskeletal conditions were recruited from the community to provide healthy reference values on postural stability. Ethics approval was obtained from the local university and hospital review boards. In accord with university and hospital policies, informed consent was received from all participants prior to their participation in the study.

Protocol

The participants with stroke and healthy older controls were tested on an EquiTest[®] system (NeuroCom International Inc.) using the Sensory Organization Test (SOT), which consists of six conditions, and has established reliability and validity.^{13–15} This system has a support surface consisting of force plates and a visual surround that can move together or independently via servomotors. The system is capable of moving proportional to the person's anterior-posterior (AP) postural sway, which is referred to as sway-referencing (i.e. sway-referenced gain of 1.0). Depending on the SOT condition, the support surface and/or the visual surround were moved (sway-referenced surface and sway-referenced surround, respectively), which serves to alter somatosensory (i.e. ankle proprioception) or visual information. Table 2 describes each of the six SOT conditions. Quiet standing with eyes open is represented in condition one. Note that vestibular information is the only accurate source of sensory information available in conditions five and six. Participants stood with their own shoes on the force plates while attached via a harness to an overhead beam. They were given instructions to maintain upright posture while looking straight ahead with their arms relaxed at their sides. Rests were given if participants requested them. The SOT protocol consisted of three, 20-second trials for each of the six conditions. The operator stopped a trial when the participant required a step to regain balance, grabbed the sides of the system or a spotter, or required support from the harness. The above scenarios were registered as a fall and that trial was given a score of zero.

The Equilibrium scores (based on an individual's postural sway) for each SOT condition were calculated by determining the maximum and minimum AP sway angles. The AP sway angle (see Figure 1) is the angle between a line projecting vertically from the center of foot support and a line from the center of foot support to the center of gravity (COG) position on the body (i.e. 55% of individual's total height).¹⁶ The center of foot support is located slightly forward of the ankle joint and is directly beneath a person's COG when they are standing erect.¹⁶ The position of the vertical projection of the COG was determined using a second-order low-pass filter from the AP center of pressure of the force plates. The AP sway angle was then determined from the relationship between the position of the vertical projection of the COG and the vector from the center of foot support to the projected COG position on the body (see Figure 1). The Equilibrium score for each trial was subsequently calculated as a percentage, which compares the peak amplitude of AP sway to the theoretical AP limits of stability using the following formula: Equilibrium score = $((12.5^\circ - [\theta_{\max} - \theta_{\min}]) / 12.5^\circ) * 100$.¹⁷ A high score of 100 represents no postural sway and lower scores indicate poor balance or postural instability. To assess individual conditions, Equilibrium scores for SOT conditions two to six were divided by the score in condition one to normalize for baseline differences (i.e. condition one) in postural sway when comparing persons with stroke with controls, as sway is increased after stroke even without manipulating the sensory environment.¹⁸

Muscle strength (i.e. isokinetic, concentric joint torque) of the paretic and non-paretic ankle, knee, and hip flexors and extensors of the persons with stroke was assessed using a Kin-Com Isokinetic Dynamometer (Chattanooga Group Inc). An angular velocity of 30-degrees per second for the ankle and 60-degrees per second for the knee and hip were used. One sub-maximal and one maximal trial for each joint and direction were completed as practice. During the maximal practice trial and subsequent three test trials, participants were instructed to "push or pull as hard as possible" throughout their range of motion. Rests were given as needed. For each movement tested a single ensemble-averaged torque-angle curve was calculated from three maximal repetitions. Subsequently, the peak torque of the torque-angle curve was extracted and normalized to the participant's body mass. This strength protocol has demonstrated high test-retest reliability (ICC > 0.95) in persons with stroke.⁵

A pressure aesthesiometer kit (8 monofilaments) was used to determine the tactile sensitivity (an indication of cutaneous sensation ability) of the persons with stroke using the "method of limits".¹⁹ Briefly, with participants facing away from the tester, the monofilaments were applied for less than a second and deformed to half their length against the plantar surface of the feet (forefoot pads). A sequence of thicker to thinner filaments was applied and the number of the monofilament that was last able to be felt was recorded. The thickest monofilament (i.e. poor tactile sensitivity) was number 8, while number 9 indicated no tactile sensation.

Statistical analyses

Due to the lack of normality in the Equilibrium scores (Kolmogorov-Smirnov test for normality, $p < 0.05$), group differences and correlations used non-parametric statistics. All

statistical analyses were performed using SPSS, version 11.5, for Windows, with an alpha level set at 0.05.

First, Mann-Whitney U tests compared the Equilibrium scores of SOT conditions two to six (i.e. five conditions) of the persons with stroke to the healthy older adult controls. Next, Chi-square tests were performed to determine differences in the proportion of fallers and repeat fallers (i.e. two or more falls) between persons with stroke and controls during the SOT over the six conditions.

To quantify the relationship between sensorimotor function and postural stability within the persons with stroke, Spearman correlations were performed on each SOT condition (non-normalized Equilibrium score data), muscle strength data (paretic and non-paretic ankle dorsiflexion, ankle plantarflexion, knee extension, knee flexion, hip extension, and hip flexion), and cutaneous sensation scores. Those variables that were significantly correlated with the SOT conditions in the univariate analysis were then entered into the stepwise multiple regression analyses to determine the predictors for the SOT conditions. A predictor was entered into the model at $p = 0.05$ and was removed at $p > 0.1$. Note that the regression procedure has the advantage of providing a predictive model; however, the correlations provide additional information regarding some variables that the regression procedure may have removed from the model due to their close relationship to the best predictor.

RESULTS

Integration of afferent information

Median (IQR) scores (non-normalized data) for each SOT condition for the persons with stroke and controls are shown in Table 3. There were no differences between persons with left and right hemiparesis or between cortical and subcortical strokes for all measures ($p > 0.05$). Mann-Whitney U tests demonstrated reduced scores for SOT condition four ($p = 0.004$), five ($p < 0.0001$), and six ($p < 0.0001$) in the persons with stroke versus controls. There were no group differences in SOT condition two ($p = 0.99$) and three ($p = 0.18$).

Table 4 shows the number of falls, number of participants who fell, and number of multiple fallers for each SOT condition. There was a total of 143 falls for the persons with stroke throughout the entire SOT protocol compared to only 15 in controls. There were also a significantly greater number of fallers and repeat fallers for the persons with stroke compared to controls ($p < 0.0001$).

Correlation of sensorimotor impairment to postural sway in stroke

Table 5 shows the correlations between muscle strength, cutaneous sensation, and the Equilibrium scores for each SOT condition in the persons with stroke. Low to moderate correlations (range $\rho = 0.33$ to 0.53) were found between some joint torques and the SOT conditions. Significant correlations occurred predominantly during the more challenging SOT conditions (i.e. 5 and 6).

The median (IQR) scores for the cutaneous sensation testing in the persons with stroke were 4 (3) and 4 (2) out of a maximum of 9 for the paretic and non-paretic limbs, respectively,

and suggestive of moderate impairment. Four persons with stroke had no cutaneous sensation on their paretic foot while seven had normal cutaneous sensation (i.e. score of 1 or 2) on the paretic foot and nine had normal cutaneous sensation on their non-paretic foot. No significant correlations were found with cutaneous sensation.

Table 6 reports the average peak torques for each joint action in the persons with stroke. Given that muscle strength had only significant contributions during the most challenging SOT conditions, a stepwise multiple regression analyses was performed to determine the predictors for the most challenging SOT condition (i.e. condition 6). The model retained the non-paretic plantarflexion and paretic knee flexion to account for 38% of the variability in the SOT condition six.

DISCUSSION

Muscle strength was only a significant factor with the more challenging SOT conditions (i.e. 4, 5, or 6). Thus, as the ground upon which persons with stroke were standing on became more unstable and sensory cues misleading, they relied more on motor function. Similarly, Lord and Menz⁸ reported that quadriceps strength only correlated with postural sway when healthy older adults stood on a compliant (or unstable) surface, but not on a level surface. However, the correlations in the present study were low (ρ 0.33 to 0.53), and in addition, muscle strengths were only able to explain 38% of the variability for the most difficult SOT condition using a multiple regression. In addition, SOT scores for the least difficult conditions were not related to muscle strength, but these scores were still lower than values from healthy older adults. Consequently, impaired sensory integration likely had a large influence on our results.

Re-weighting incoming sensory information requires sufficient cognitive processing resources and thus is attention-demanding.²⁰ In stroke, the resulting hemiparesis may require these individuals to use a larger amount of attention resources to maintain postural stability. Further, damage to cortical areas may reduce cognitive processing capacity and slow sensory integration time. Using a dual-task paradigm, Brown et al.²¹ demonstrated increased reaction times (i.e. verbal response to a visual stimulus) among persons with stroke during various postural tasks compared to healthy older adults.

Misleading sensory cues must be inhibited, possibly through deactivation of specific brain regions, whereas accurate sensory information must be selected. Recently, in a series of PET activation studies in humans, it was demonstrated that visual motion stimulation not only activated visual cortical areas, it also resulted in reciprocal inhibition in that the parieto-insular vestibular cortex (PIVC) was deactivated.²² Vice versa, vestibular stimulation through caloric irrigation activates vestibular cortical regions while simultaneously deactivating occipital cortex regions.²² Thus, when challenged with a task where redundant sensory systems are not available, persons with stroke may require more time to process and integrate sensory information or may be unable to deactivate the necessary cortical areas for re-weighting this sensory input. As a result, stability is compromised and falls occur. Nearly 73% of the persons with stroke fell at least once throughout the SOT protocol and 60% fell multiple times (Table 4). These falls were most prevalent during sensory conflict conditions.

Individuals with vestibular deficits frequently fall during conditions five and six of the SOT when vestibular cues are the only accurate source of information regarding the position of the body in space.²³ Scores were severely attenuated in these conditions in persons with stroke compared to controls and falls were more numerous. Thus, persons with stroke may be less able to use vestibular cues. It is important to note that the SOT protocol does not allow one to eliminate vestibular cues; therefore, we cannot conclude that vestibular processing is impaired but rather, only speculate that it contributes to increased postural sway in stroke.

By examining the relationship between the vestibulo-ocular reflex and stability (assessed through various standing tasks with eyes open and closed), Catz et al.¹⁰ found that loss of balance following stroke may be related to impaired cortico-vestibular modulation of vestibular function. In a recent study in persons with stroke, Bonan et al.¹¹ found a trend towards greater postural sway in persons with stroke affecting the PIVC, the cortical area believed to represent the integration centre for vestibular processing.²⁴

Although cutaneous sensation from the plantar surface of the foot is known to play a large role in controlling postural sway in healthy individuals,^{25,26} our results showed that our measure of sensation was not correlated to sway in any of the SOT conditions. This may be due to the fact that the tactile measure that we assessed was during a non weight-bearing static posture and is not reflective of the cutaneous requirements during challenges to standing balance. Alternatively, the large contribution from muscle strength, ankle proprioception, and the ability to integrate sensory information may reduce the role of cutaneous sensation in controlling postural sway.

A limitation of this study was that sway and muscle function were assessed in the AP direction only. It is possible that even greater deficits may have been found in persons with stroke in the medial-lateral direction because of the known medial-lateral weight-bearing asymmetry.²⁷

In conclusion, impairments in re-weighting/integrating afferent information, in addition to muscle weakness appear to contribute to postural instability and falls in persons with stroke. Hu and Woollacott²⁸ suggest the use of multi-sensory training could improve balance performance in older adults. The same approach may also be effective in persons with stroke.

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Figure 1.

Anterior-posterior (AP) sway angle. AP sway angle was calculated from the relationship between the position of the vertical projection of the center of gravity (COG) and the vector from the center of foot support to the projected COG position on the body. This figure was modified from NeuroCom International Inc.¹⁶

Table 1

Participant characteristics of the persons with stroke and healthy older adult controls.

	Stroke Mean (SD) or n	Controls Mean (SD) or n
Gender, M/F	27/13	27/13
Age, yrs	67.1 (8.2)	67.1 (7.9)
Height, cm	169.3 (9.7)	172.3 (8.1)
Mass, kg	78.9 (14.6)	74.5 (14.7)
Time Since Stroke, yrs	3.6 (2.2)	N/A
Hemiparetic Side, R/L	14/26	N/A
AHASFC, I/II/III/IV/V	9/11/16/3/1	N/A
Type of Stroke	23 ischemic 17 hemorrhagic	N/A
Stroke Location	16 cortical 24 subcortical	N/A

Abbreviations: M = male; F = female; R = right; L = left; NA = not applicable; AHASFC = American Heart Association Stroke Functional Classification

Table 2

Sensory Organization Test (SOT) conditions

SOT Condition	Sway-referencing	Normal	Sensory Systems Altered	Absent
1	None	All	None	None
2	None	Somatosensory & Vestibular	None	Visual
3	Surround	Somatosensory & Vestibular	Visual	None
4	Surface	Visual & Vestibular	Somatosensory	None
5	Surface	Vestibular	Somatosensory	Visual
6	Surround & Surface	Vestibular	Visual & Somatosensory	None

Table 3

Median (IQR) of Equilibrium scores (non-normalized) for each SOT condition.

SOT Condition	Health Older Adults (N = 40)	Persons with Stroke (N = 40)
1	95 (3.25)	92 (4.5)
2	89 (3.5)	86 (7.5)
3	90 (5)	83 (11.75)
4	82.5 (7.25)	75 (13.25)
5	59 (10.5)	37.5 (58.25)
6	62 (10.25)	0 (58.25)

Table 4

Falls during the SOT for the persons with stroke (N = 40) and controls (N = 40).

Condition	Total Falls		Fallers		Repeat Fallers	
	Stroke	Controls	Stroke	Controls	Stroke	Controls
1	0	0	0	0	0	0
2	5	0	3	0	1	0
3	12	1	6	1	5	0
4	11	0	6	0	3	0
5	55	7	24	7	18	0
6	60	7	36	7	21	0
Total	143	15	29 ^{*,‡}	11 [*]	24 ^{*,‡}	3 [‡]

* Individuals who fell at least once during the six SOT conditions

‡ Individuals who fell multiple times during the six SOT conditions

[‡]Significant difference between stroke and controls, p < 0.0001

Table 5

Spearman correlations between muscle strength, foot sensation, and the six SOT conditions in the persons with stroke.

Measure	SOT Conditions					
	1	2	3	4	5	6
Paretic dorsiflexion	-0.31	0.16	0.09	-0.15	0.32	0.27
Paretic plantarflexion	-0.25	0.09	0.05	-0.11	0.33*	0.29
Paretic knee extension	-0.19	0.19	0.12	0.14	0.43**	0.53**
Paretic knee flexion	-0.24	0.13	0.10	0.16	0.45**	0.49**
Paretic hip extension	-0.16	0.03	-0.09	0.19	0.16	0.30
Paretic hip flexion	-0.12	-0.04	-0.09	0.16	0.16	0.24
Non-paretic dorsiflexion	0.23	0.15	0.18	0.39*	0.28	0.30
Non-paretic plantarflexion	0.04	0.12	0.11	0.10	0.26	0.26
Non-paretic knee extension	0.04	-0.004	0.030	0.12	0.21	0.23
Non-paretic knee flexion	0.03	-0.10	0.17	0.40*	0.21	0.47**
Non-paretic hip extension	-0.02	0.07	-0.02	0.17	0.12	0.26
Non-paretic hip flexion	0.07	0.04	0.16	0.42**	0.17	0.35*
Paretic foot sensation	-0.13	-0.23	-0.20	0.16	0.02	0.08
Non-paretic foot sensation	-0.11	-0.06	-0.04	0.10	0.18	0.12

Note: values are Spearman rho value

*
p < 0.05

**
p < 0.01

Table 6

Average (standard deviation) peak joint torques for the persons with stroke.

Muscle	Peak Joint Torque (Nm/kg)	
	Non-paretic Limb	Paretic Limb
Ankle Dorsiflexors	0.237 (0.082)	0.150 (0.118)
Ankle Plantarflexors	0.346 (0.203)	0.228 (0.162)
Knee Flexors	0.525 (0.237)	0.310 (0.157)
Knee Extensors	0.847 (0.367)	0.584 (0.270)
Hip Flexors	0.645 (0.234)	0.529 (0.192)
Hip Extensors	0.688 (0.279)	0.641 (0.247)