Voluntary stepping behavior under single- and dual-task conditions in chronic stroke survivors: A comparison between the involved and uninvolved legs

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ABSTRACT

Objective: If balance is lost, quick step execution can prevent falls. Research has shown that speed of voluntary stepping was able to predict future falls in old adults. The aim of the study was to investigate voluntary stepping behavior, as well as to compare timing and leg push-off force–time relation parameters of involved and uninvolved legs in stroke survivors during single- and dual-task conditions. We also aimed to compare timing and leg push-off force–time relation parameters between stroke survivors and healthy individuals in both task conditions.
Methods: Ten stroke survivors performed a voluntary step execution test with their involved and uninvolved legs under two conditions: while focusing only on the stepping task and while a separate attention-demanding task was performed simultaneously. Temporal parameters related to the step time were measured including the duration of the step initiation phase, the preparatory phase, the swing phase, and the total step time. In addition, force–time parameters representing the push-off power during stepping were calculated from ground reaction data and compared with 10 healthy controls.
Results: The involved legs of stroke survivors had a significantly slower stepping time than uninvolved legs due to increased swing phase duration during both single- and dual-task conditions. For dual compared to single task, the stepping time increased significantly due to a significant increase in the duration of step initiation. In general, the force time parameters were significantly different in both legs of stroke survivors as compared to healthy controls, with no significant effect of dual compared with single-task conditions in both groups.
Conclusions: The inability of stroke survivors to swing the involved leg quickly may be the most significant factor contributing to the large number of falls to the paretic side. The results suggest that stroke survivors were unable to rapidly produce muscle force in fast actions. This may be the mechanism of delayed execution of a fast step when balance is lost, thus increasing the likelihood of falls in stroke survivors.

1. Introduction

Stroke survivors are at high risk for falls. The incidence of falling among stroke survivors ranges from 25% to 73% (Forster and Young, 1995; Teasell et al., 2002; Ugur et al., 2000), while 30% of adults older than 65 experience at least one fall every year (Burt and Fingerhut, 1998). Patients with stroke have a 4-fold increased risk of hip fracture on the paretic side because of a tendency to fall to that side (Mulley and Espley, 1979) and because there is a tendency to develop osteoporosis on the affected side (Ramnemark

et al., 2000). Other serious fall-related consequences include decreased independence in daily living activities and participation in society (Davenport et al., 1996), and even death (Langhorne et al., 2000).

Once a fall is initiated, rapid stepping is a critical skill for successful balance recovery (Melzer et al., 2007). Voluntary step execution times in the uninvolved leg of stroke survivors were found to be significantly delayed compared with age-matched healthy controls (Melzer et al., 2009). Thus, delayed step times were suggested to be a major contributor to falls in stroke survivors. In the current research we aimed to explore differences in voluntary step behavior, a motor task of critical importance to prevent a fall from occurring, using the involved and uninvolved legs and to identify which of the step phases – step initiation-, preparation- or swing-phase – are markers for increased stepping time and thus, risk of falling. In addition, we asked whether a concurrent

attention-demanding task delayed the execution of a voluntary step in both the involved and uninvolved legs. We also aimed to explore whether differences in leg push-off power is one of the underlying mechanisms contributing to slower voluntary stepping speed of stroke survivors compared to healthy individuals in both task conditions. Leg push-off power during execution of a rapid voluntary step was measured using ground reaction force data and not dynamometric techniques, which measure specific muscle strength, neglecting the importance of studying power during the actual action (e.g., the leg push-off the ground during stepping performances). In particular, we aimed to verify whether the generation of propulsive forces and the time of force application differ between involved and uninvolved legs of stroke survivors and healthy controls during the push-off phase in a rapid step, and in what aspects they differ. These parameters may reflect the ability to generate muscle power that is related to the rapid production of the muscle strength needed during the execution of rapid stepping and fall avoidance. Reduced leg push-off power might be one of the underlying mechanisms contributing to slower voluntary stepping speed in stroke survivors. Results may help to develop and implement effective strategies to minimize risk of falls among stroke survivors, which is essential to minimize future health costs and human suffering.

First, we hypothesized that the voluntary step times would be slower on the involved side due to increased duration of step initiation, preparation, and swing phases, thus explaining the increased risk of fall on the paretic side. Second, we hypothesized that propulsive forces (e.g., push-off force–time parameters) during stepping will be lower in both legs of stroke survivors compared with healthy controls. Finally, we hypothesized that under concurrent attention-demanding dual-task condition stepping times and propulsive forces will be reduced in both legs of stroke survivors and in healthy controls.

2. Methods

2.1. Subjects and procedure

After approval by the Helsinki Ethics Committee, 7 male and 3 female stroke survivors (61.7 ± 10 years old) 6.7 ± 4.1 years post-stroke (Table 1), and 10 healthy age-sex matched controls (61.7 ± 7.6 years old) who signed informed consent forms, were recruited. Stroke survivors were recruited based on the following criteria: at least 1-year post-stroke and hemiparetic, a Mini-Mental State Examination score greater than 24 indicating the absence of dementia, absence of serious visual impairment or color blindness, ability to ambulate independently (cane allowed but not walker), no previous or additional neurologic disorder.

Our sample size estimation was based on work by Melzer et al. (2009) showing that voluntary step times under dual-task conditions in stroke survivors were 1445 ms compared with 1006 ms in healthy controls (439 ms difference, SD 258 ms). Using the above numbers for a two-sided estimate at a significance level of

0.05 and 90% power, a minimum of six subjects would be required to detect changes in step execution time. Ten subjects were recruited to increase the power of the test.

2.2. Instrumentation and data analysis

Center of pressure and ground reaction force data during step execution trials were collected and sampled at a frequency of 100 Hz, using a portable Kistler 9287 force platform (Kistler Instrument Corp., Winterthur, Switzerland). Subjects were instructed to stand bare foot in a standardized stance with the hips externally rotated 10° and their heels separated by 6 cm. During the single-task trials, subjects were asked to view an 'X' projected at eye level onto a wall 3 m in front of them and to step as quickly as possible following a distinct tap on the heel of the stepping foot provided manually by the rater.

Twelve step execution trials were performed in randomized order, three forward and three backward, for each leg, six stepping trials with the involved leg and six stepping trials with the uninvolved leg; healthy control subjects were instructed to step with their dominant leg. Because different step sizes could have influenced the step execution times, the subjects were instructed to step outside the force plate. Subjects were allowed to practice to become familiar with the test situation and to ensure step clearance of the force platform before performing the stepping trials. Following completion of the 12 single-task trials, subjects repeated the protocol under dual-task conditions performing a modified-Stroop test. The modified-Stroop test consisted of a 5 by 5 matrix with names of colors where the color of the ink was always different from the name of the color. For example, the word "red" was printed in yellow ink. Subjects were asked to step as quickly as possible from the force plate while reading out loud the color of the ink of the projected color name. The modified-Stroop test was used because it requires focused attention and few instructions to perform. In addition, it requires only direct verbal responses and it does not address memory, which may be impaired in stroke survivors. Steps included in the analysis were 50–60 cm long; steps that were longer or shorter were extracted from the analysis. Short steps occurred in 15% of the trials during the single-task condition and 32% of the dual-task trials (between 1 and 3 of the 6 trials) only on the involved side of stroke survivors in both female and male subjects. Force platform data were analyzed using code written in Matlab (Math Works Inc., Cambridge, MA, USA) to extract temporal parameters: step initiation, preparation, and swing phases, and foot-contact time (Fig. 1). The tap cue was detected as the onset of the spike (greater than three standard deviations from the average baseline noise) in the ground reaction forces in the anteroposterior direction. Step initiation was defined at the first mediolateral deviation of center of pressure (COP) towards the swing leg (more than 4 mm from the average baseline sway prior to tap). Foot-off time was defined by a sudden change in the slope of COP towards the stance foot in the mediolateral direction. Foot-contact time was defined as the onset of unloading in the vertical ground reaction force. The step initiation phase was calculated as the time from tap onset to step initiation. The preparation phase was calculated as the time from step initiation to foot-off; swing phase was calculated as the time from foot-off to foot-contact. Additional code written in Matlab was used to compute the following leg push-off power parameters during the preparation and swing phases of step execution: (1) AP peak force (N): maximal value of force increase in the anterior–posterior direction, which is the direction of the intended step; (2) normalized vertical peak force (body weight units), maximal value of force increase in the vertical direction; (3) time to anterior–posterior peak force (ms): the time to the maximum anterior–posterior force after the onset of the preparation and swing phases; (4) time to vertical

Table 1
Group characteristics shown as means ± 1 SD.

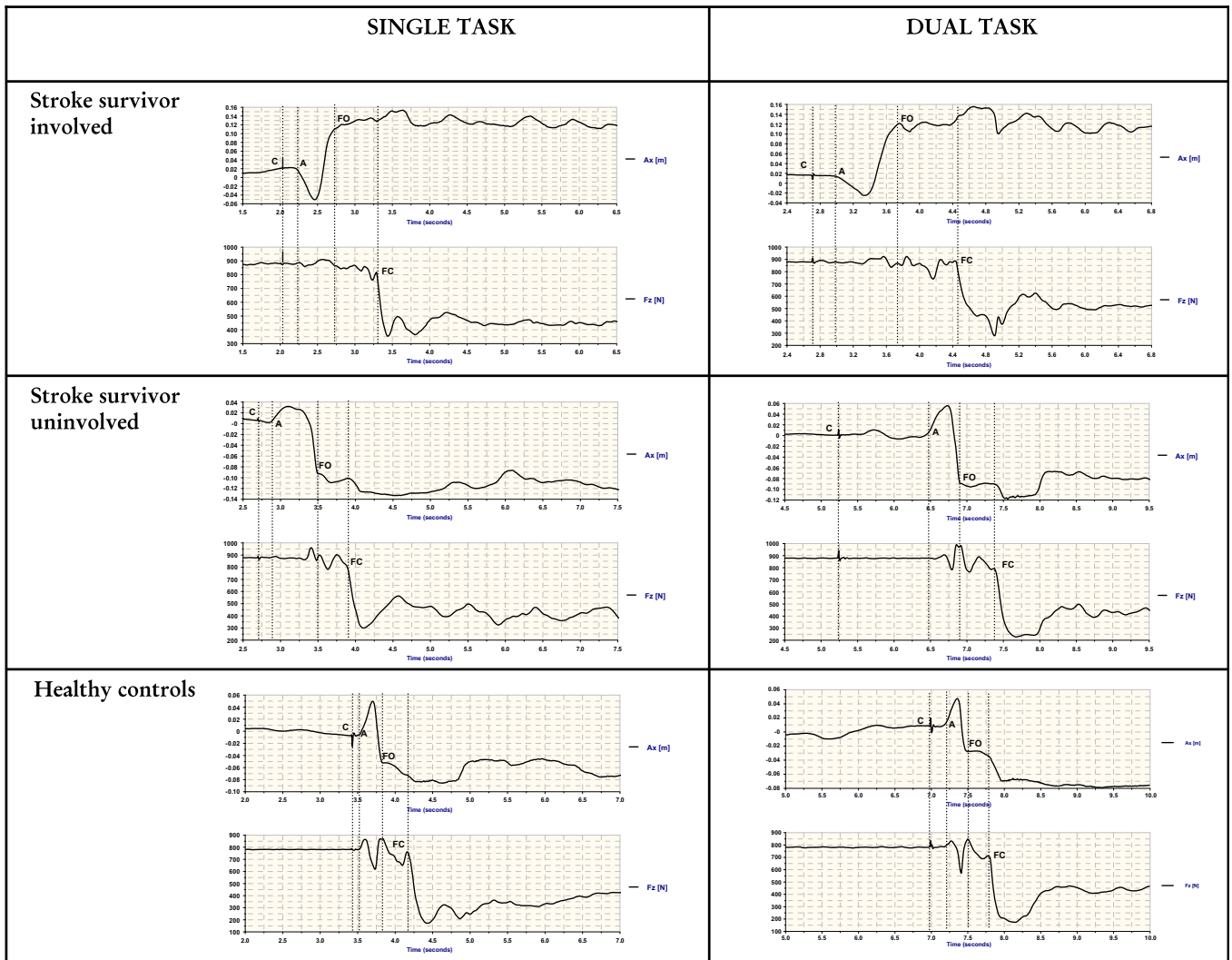|	Stroke survivors	Healthy controls
Age (years)	61.7 ± 10	61.7 ± 7.6
Weight (kg)	80.5 ± 21.8	75.8 ± 12.7
Height (cm)	171.1 ± 6.1	173 ± 3.4
BMI	27.9 ± 6.7	25.9 ± 5.1
MMSE	27.4 ± 1.8	29.2 ± 1.2
BBS	46 ± 4.5	56
Years post-stroke	6.7 ± 4.1	0

Fig. 1. Example of forward step execution data for a stroke survivor with the involved leg (upper row), uninvolved leg (middle row) and healthy control subject (lower row). Ax = Mediolateral center of pressure; Fz = vertical ground reaction forces; mm = millimeter; N = Newton. The following events are marked with lines across all figures; tap cue is detectable especially in Fy (C); initial deviation of COP in mediolateral direction (A); foot-off (FO); foot-contact (FC). Note the differences in swing phase duration between the involved leg and uninvolved leg (distance between FO and FC). Also the differences in initiation phase duration (distance between A and FO) between the single- and dual-task conditions in the involved leg and uninvolved leg of stroke survivor and healthy control subject. See text for further details.

peak force: the time to the maximum vertical force after the onset of the preparation and swing phases. Differences in these parameters may be attributed to decreased ability to reach peak force values in short time intervals.

2.3. Statistical analysis

Because the variables were not normally distributed (Shapiro–Wilk statistics), Mann–Whitney *U*-test was used to detect significant differences between the involved and uninvolved legs, and between stroke survivors and their age-sex matched healthy controls. Wilcoxon signed-rank tests were used to detect significant differences between task conditions (single vs. dual). Since there were no significant differences between forward and backward stepping in all step variables (e.g., $p = .14–.98$ for the involved side and $p = .25–.72$, for the uninvolved side) an average of each variable across all six trials (3 forward and 3 backward) during single-task and dual-task conditions was used to represent each subject. The temporal dependent variables were: (1) the duration of initiation phase, (2) the duration of preparatory phase, (3) the duration of swing phase, and (4) the total step time. The force–time relation

parameters included: (1) AP peak force (N), (2) normalized vertical peak force (times body weight units, TBW), (3) time to anterior–posterior peak force (ms), and (4) time to vertical peak force (ms). Statistical significance was accepted at $p < .05$. SPSS was used for statistical analyses (SPSS version 17, SPSS Inc., Chicago, IL).

3. Results

3.1. Stroke survivors vs. healthy controls

There was a statistically significant decrease across all step execution phases for both task conditions between stroke survivors and healthy controls (Table 2). In general, stroke survivors compared with healthy controls showed a statistically significant longer time to generate peak forces in the preparation and swing phases, in both legs, during single- and dual-task conditions (Table 3A and B). For example, the time to AP peak forces in the preparation and swing phases during single-task stepping were 80% and 162% longer, respectively, in the uninvolved leg compared with healthy controls ($p = .009$ and $p = .01$, respectively, Table 3A and B). Also the time to AP peak forces in the preparation and

Table 2
Temporal effects of modified-Stroop test.

	Involved leg		Uninvolved leg		Healthy controls	
	Single task	Dual task	Single task	Dual task	Single task	Dual task
Initiation phase (ms)	359 ± 290[c]	485 ± 293[b,c]	369 ± 232	530 ± 309[b]	148 ± 28	224 ± 74
Preparatory phase (ms)	667 ± 215[c]	727 ± 299[c]	640 ± 183	710 ± 249	378 ± 66	415 ± 35
Swing phase (ms)	550 ± 212[a,c]	541 ± 209[a,c]	377 ± 124	388 ± 115	287 ± 53	307 ± 75
Total step time (ms)	1575 ± 568[a,c]	1750 ± 548[b,c]	1386 ± 454	1630 ± 575[b]	813 ± 131	946 ± 148

Note: Voluntary step execution parameters for involved and uninvolved legs of stroke survivors and healthy controls in both task conditions.
Values are means ± 1 SD in milliseconds.
[a] Significant differences between involved and uninvolved ($p \leqslant 0.05$).
[b] Significant differences between dual- and single-task conditions ($p \leqslant 0.05$).
[c] Indicates statistically significant differences between stroke survivors and healthy controls ($p \leqslant 0.05$).

Table 3
Mean push-off force–time parameters during execution of voluntary rapid stepping for involved and uninvolved legs of stroke survivors and healthy controls during single- and dual-task condition. Values in preparation and swing phases represent averages from 6 trials ± 1 SD (average of 3 forward and 3 backward stepping trials).

Power parameters	Hemiparetic uninvolved leg		Hemiparetic involved leg		Healthy dominant leg	
	Step phases					
	Preparation phase	Swing phase	Preparation phase	Swing phase	Preparation phase	Swing phase
(A) Single task						
Anterior–posterior peak force (N)	43.7 ± 10.2[c]	53.7 ± 16.3[c]	38.2 ± 21.9[c]	61.8 ± 19.3	74.4 ± 22.7	73.8 ± 18.8
Normalized vertical peak force (TBW)	1.06 ± 0.02[c]	1.06 ± 0.05	1.05 ± 0.01[c]	1.06 ± 0.05	1.09 ± 0.04	1.06 ± 0.05
Time to anterior–posterior peak force (ms)	505.3 ± 187[c]	294.5 ± 171[c]	464.7 ± 141[c]	525.9 ± 274[a,c]	320.8 ± 62	127.7 ± 70
Time to vertical peak force (ms)	525.6 ± 208[c]	208.9 ± 159[c]	454.1 ± 157[c]	268.4 ± 196[a,c]	274.8 ± 64	71 ± 36
(B) Dual task						
Anterior–posterior peak force (N)	42.6 ± 9.1[c]	59.9 ± 16.2	27.7 ± 7.6[c]	52.6 ± 14.5	63.7 ± 19.5	65.8 ± 23.6
Normalized vertical peak force (TBW)	1.05 ± 0.02	1.04 ± 0.02	1.05 ± 0.01	1.04 ± 0.03	1.06 ± 0.04	1.03 ± 0.06
Time to anterior–posterior peak force (ms)	483.8 ± 104[c]	300.9 ± 177[c]	490.8 ± 61[c]	460.3 ± 225[c]	380 ± 49[b]	147.8 ± 120
Time to vertical peak force (ms)	462.4 ± 133[c]	151 ± 116	441.3 ± 132[c]	218.8 ± 155	308.5 ± 91	153.3 ± 117[b]

ms – millisecond; N – Newton; N m/s – Newton ∗ meter/second; TBW – times body weight.
[a] Indicates statistically significant differences between involved and uninvolved legs of stroke survivors ($p \leqslant 0.05$).
[b] Indicates statistically significant differences between dual- and single-task conditions ($p \leqslant 0.05$).
[c] Indicates statistically significant differences between stroke survivors and healthy controls ($p \leqslant 0.05$).

swing phases during single-task condition were 73% and 331% longer using the involved leg compared with healthy controls ($p = .01$ and $p < .001$, respectively, Table 3A and B). The normalized vertical peak force during swing was not statistically different between stroke survivors and controls in both task conditions. However, the AP peak force was significantly lower in both involved and uninvolved legs of stroke survivors compared with healthy controls, especially during the preparation phase in single- and dual-task conditions ($p < .05$).

3.2. Involved vs. uninvolved legs

During the single-task condition the swing phase duration was 31.5% longer for the involved compared with the uninvolved leg ($p = .047$), with no significant differences in the step initiation and preparation phases. The involved leg of stroke survivors showed 12% slower stepping time ($p = .047$; Table 2). During the swing phase of single-task stepping, the time to anterior–posterior peak force and the time to vertical peak force were significantly longer using the involved leg compared with the uninvolved leg of stroke survivors (64% and 42%, respectively, $p < .05$, Table 3A).

Table 2 shows that during dual-task condition the swing phase duration was 18.3% longer for the involved compared with uninvolved leg ($p = .05$), with no significant differences in all other step phases including step time ($p = .20$). In addition, no significant differences were found in all push-off force–time parameters between involved and uninvolved legs of stroke survivors during the dual-task condition (Table 3B).

3.3. Effect of concurrent cognitive task

During the concurrent cognitive task, the involved and uninvolved legs show a significant increase in step initiation phase (35%, $p = .007$ and 43%, $p = .005$, respectively) compared with single-task condition, with no significant differences in the duration of the preparation and swing phases. These resulted in 11% and 17.6% increases in stepping time (i.e., foot-contact time) using the involved and uninvolved legs ($p = .037$ and $p = .013$, respectively; Table 2). For dual- compared with single-task there were no significant differences between both task conditions during the preparation and swing phases in all push-off force–time parameters (Table 3A and B).

4. Discussion

The present findings demonstrate that performance of a concurrent attention-demanding task reduces the speed of voluntary stepping in chronic stroke survivors as found previously during standing (Bensoussan et al., 2007), walking (Plummer-D'Amato et al., 2008), or stepping with the uninvolved leg (Melzer et al., 2009). Here we extend these findings and demonstrate that the involved leg had a significantly slower stepping time (i.e., foot-contact time) compared with the uninvolved leg; this can be attributed to increased swing phase duration and not due to increased step initiation or step preparation phase durations. Analyzing the ground reaction force data, we also found that during the performance of voluntary stepping, the time to peak force is the power parameter that is most affected by a hemiparesis compared

with healthy controls, while peak forces, especially vertical peak force, were less affected. In addition, the dual-task condition markedly increased stepping times in both legs of stroke survivors due to slower step initiation phase duration; however, there was almost no influence on propulsive forces generated during the preparation and swing phases in both groups.

Our results show that step execution times, especially using the involved leg of chronic stroke survivors, were well above the 1100 ms cut-off time that was found to increase the risk of fall 5-fold in old adults (Melzer et al., 2007). These findings suggest that the tendency to fall to the involved side in stroke survivors may result from an inability to generate force rapidly and swing the involved leg appropriately, and execute a rapid and effective step response during both single task and during a performance of a concurrent secondary task. Kirker et al. (2000) found very impaired or absent hemiplegic gluteus medius and hip adductor muscles during gait initiation. Although the stepping times were not within the scope of their study, it can be clearly seen from the ground reaction force data in Fig. 4 in their paper (Kirker et al., 2000) that preparatory phase duration, i.e., sideways weight shift, was similar between legs, while swing phase duration of the involved leg was at least twice as long as with the uninvolved leg. The longer swing phase duration seen in our study and that of Kirker et al. (2000) may result from weak and delayed response of leg push-off muscles (e.g., ankle plantar-flexors) during the preswing phase or due to weak hip flexors during the swing phase of the involved leg, and/or weak muscles in the uninvolved leg that pushes the body in the direction of movement during the during swing phase of the involved leg. Our findings demonstrated that the ability of stroke survivors to generate peak forces rapidly in both legs and during both task conditions was slower than healthy controls. These results suggest that the mechanism contributing to slower voluntary stepping in stroke survivors is related to both timing and power (i.e., time to peak force), and also from reduction of muscle force capability especially in the direction of movement (i.e., AP peak forces). In their review, Geurts et al. (2005) reported a delayed, temporally disrupted, and weakened short-latency, as well as medium- and long-latency lag in EMG responses on the paretic side of stroke survivors in reaction to movements of the support surface. We interpret these findings as a decreased ability of the involved side to contract muscles fast enough to exert the mechanical force required to step rapidly and prevent a fall when balance is lost. We suggest that adequate muscle force as well as proper timing is critical for a rapid generation of propulsive force during swing phase. It is unknown how effectively therapists can train patients to modify their motor programs.

We hypothesized that the uninvolved leg would show less interference effects in dual task. The results illustrate similar level of interference effects of the dual-task test condition on the duration of the step initiation phase in both legs (Table 2); this suggests that the central reorganization process after stroke influences both involved and uninvolved sides similarly. The results also suggest that during the preparation and swing phases of dual-task stepping, stroke survivors focused their attention more strongly on the motor act, (i.e., posture first strategy), thus no interference effects of a concurrent cognitive task on temporal events and force–time relations of both legs were found. This behavior is seen in age-comparative laboratory research on cognitive-sensorimotor dual-task situations, showing that weak old adults, compared with young participants, tend to focus their attention more strongly on the sensorimotor tasks when both tasks are very resource demanding (Huxhold et al., 2006), thus investing less resource into the cognitive task. This potential differential-emphasis behavior may explain the insignificant differences in the temporal and force time relations during preparation and swing phases between single-

and dual-task conditions in both legs of stroke survivors and healthy controls.

Fall risk is both common and modifiable; clinicians need methods to treat post-stroke patients who are at the greatest risk of falling. However, ongoing treatment programs for stroke survivors are not routinely available. There is evidence that an exercise program can enhance functional abilities after stroke (Legg et al., 2004). However, it is less clear whether exercise can prevent falls among stroke survivors. A structured adaptive physical activity produces improvements in balance, gait, fitness, and ambulatory performance but not in falls efficacy or free-living daily step activity (Michael et al., 2009). This is not surprising, since according to the basic principle of physical training and exercise physiology, physical interventions must incorporate exercises that closely mimic and provide a challenge to the successful performance of balance recovery tasks such as stepping skills.

The study has several limitations. First, the data came from a fairly small sample that was drawn from defined relatively independent stroke survivors; these results cannot be generalized to extremely weak or institutionalized stroke survivors. Second, cognitive performance was not assessed in the present study so we do not know how much of the delay seen using the involved and uninvolved legs was due to attentional demands. However, we can conclude that both legs of stroke survivors were affected equally, i.e., the interference effects of dual and single tasks were similar. Third, since the force–time relations of voluntary stepping were analyzed using ground reaction force plate data and not EMG, we cannot rule out that the longer swing phase duration seen in our study may have resulted from weak and/or delayed response involving hip flexors compared with uninvolved legs. Further study should involve larger sample sizes and less healthy or institutionalized stroke populations. Falls follow-up studies are needed to determine if stepping behavior can predict falls in stroke survivors. In addition, randomized controlled studies are needed to determine whether step training increases the speed of effective stepping and reduces the number of falls in stroke survivors.

In conclusion, the speed of voluntary stepping is significantly slower in the involved leg of stroke survivors due to increased swing phase duration resulting from the inability to generate peak forces rapidly. This may lead to an increased tendency to fall to the involved side.

Acknowledgements

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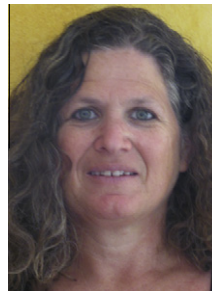
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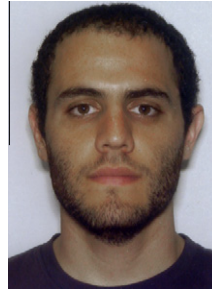
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