
Objective: To investigate voluntary step behavior of chronic stroke survivors during single- and dual-task conditions and compare the results to healthy age- and sex-matched controls.

Design: Case-control.

Setting: Laboratory-based study.

Participants: Chronic stroke survivors (n=16) and healthy controls (n=16).

Interventions: Not applicable.

Main Outcome Measures: Forward and backward rapid voluntary stepping were performed as a reaction time task under 2 conditions: (1) awaiting a cutaneous cue (single task), and (2) awaiting a cutaneous cue while performing an attention-demanding task. Step initiation, preparatory and swing phases, foot-off time, and foot-contact time were extracted from center of pressure and ground reaction forceplate data.

Results: Chronic stroke survivors were significantly slower than healthy controls in all step parameters under single- and dual-task conditions. For dual compared with single task, the foot-contact time increased from 1295ms to 1445ms (12%) in chronic stroke survivors and from 876ms to 1006ms (15%) in controls.

Conclusions: The significant increase in step phase’s duration during single- and dual-task conditions may be a factor contributing to the large number of falls seen in stroke patients. The interference effects of attention-demanding task were similar between groups, suggesting that both groups used similar strategies. Future research should determine whether step training can improve step decrements in chronic stroke survivors.

Key Words: Accidental falls; Rehabilitation; Stroke.

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BALANCE CONTROL is the foundation of our ability to move and function independently; impaired balance has been correlated with an increased risk for falls and a resulting increase in mortality in those who are prone to falling. Falls are the leading cause of injury-related visits to emergency departments and the primary etiology of accidental deaths in persons over the age of 65 years. Stroke commonly disrupts balance, postural responses, and perceptual disturbances, which may increase the risk of falls. Accordingly, stroke patients would be expected to be at risk for falls and consequently for injuries. Falling has been identified as a major complication in stroke survivors; falls were reported by 40% of subjects, and 22% reported several falls. The risk of falling at least once was more than twice as high for noninstitutionalized people with stroke. Patients with stroke have up to a 4-fold increased risk of hip fracture on the paretic side because of their tendency to fall to the affected side and osteoporosis on the paretic side. Hip fractures are the leading fall-related injury; they result in prolonged hospitalization and thus are a widespread threat to patient health and survival. The reported prevalence of previous stroke among patients with hip fracture ranges from 3% to 19%. Hip fracture survivors experience a 10% to 15% decrease in life expectancy and a significant decline in overall quality of life.

Falls occur during common daily activities, such as walking or changing position, tripping, or tangling the feet. Once a fall is initiated, rapid step execution is a critical skill for successful balance recovery. Simultaneous performance of cognitive and postural tasks has been suggested as a potential contributor to falls. However, laboratory-based studies of stepping behavior in stroke patients have commonly been single-task in nature; that is, subjects can focus their cognitive attention on performing the upcoming motor task. In a real-life situation, however, the requirement to step quickly commonly occurs under more complicated circumstances, when cognitive attention is focused elsewhere (eg, watching traffic, reading street signs or ads, talking while walking), not on performing a specific motor task. The influence of attention-demanding tasks on postural control in stroke survivors has been demonstrated in previous studies. Hyndman et al found that in the single-task condition, people with stroke had reduced velocity and stride length and a longer 5m walk time than controls. In the dual-task condition, gait slowed in both groups (stride length, velocity, and walk time). Bowen et al found that performing a verbal cognitive task while walking adversely affected stroke patients’ balance and gait velocity. Yang et al found that subjects with stroke, including the full community members who were able to walk/ambulate, have difficulty performing 2 motor tasks concurrently. Haggard et al found a 7% decrease in stride duration under dual-task conditions compared with...
single-task conditions. Stroke patients may exhibit slower stepping times, especially while conducting an additional distracting task, which may increase fall risk. Consequently, there is a need to investigate stepping behavior in stroke survivors during attention-demanding tasks.

Most theories on cognitive function conclude that the available processing resources are limited; as a result, resource competition may occur during the performance of more than 1 task, leading to task interference and difficulty in performing motor tasks.\(^2\)\(^1\) If a step is required to prevent a fall under attention-demanding circumstances, a delay in step execution may be the direct cause of a fall and the injuries that result.

In the current study, we asked whether the ability to quickly step—a motor task of critical importance to prevent a fall from occurring—was different in a group of chronic stroke survivors and healthy age- and sex-matched controls. In addition, we asked whether an attention-demanding task would delay the execution of a voluntary step in chronic stroke survivors.

**METHODS**

**Subjects and Procedures**

This study, which was approved by the local ethics committee (Helsinki Ethics Committee in Soroka University Medical Center, Beer-Sheva, Israel), was entered and completed by 16 hemiparetic subjects (mean ± SD, 64.4±9.9; age range, 46–77y) who were 7.3 years poststroke, and 16 healthy controls matched for age and sex (64.8±10.8; age range, 43–81y). All participants provided informed consent in accordance with approved procedures by the Helsinki Committee in Soroka University Medical Center (table 1). Chronic stroke survivors were recruited from members of Ne’eman Association for Stroke Survivors, and healthy control subjects were recruited from senior community centers, from senior living facilities, and from the university population. Chronic stroke survivors were included on the basis of the following criteria: at least 1 year poststroke and being hemiparetic, a Mini-Mental State Examination score of more than 24, indicating the absence of dementia,\(^2\)\(^2\) absence of serious visual impairment or color-blindness, and the ability to ambulate independently (cane allowed, but not walker). Healthy controls were included on the basis of the same criteria as chronic stroke survivors and had no previous neurologic disorders.

Our sample size estimation was based on work by Melzer et al\(^1\)\(^6\)\(^,\)\(^2\)\(^3\) that showed that voluntary step time under dual-task condition in older adults who did not fall were 18% faster than those who reported at least 2 falls during the past half year (346ms difference; SD, 340ms). By using the above numbers for a 2-sided estimate at a significance level of .05 and 80% power, a minimum of 16 subjects would be required to detect changes between chronic stroke survivors and controls.

**Instrumentation and Data Analysis**

COP and ground reaction force data during step execution trials were measured with a portable Kistler 9287 force platform. Subjects were instructed to adopt a standardized stance with their feet abducted 10° and their heels separated 6cm mediolaterally.\(^1\)\(^6\)\(^,\)\(^2\)\(^3\) A total of 3 forward and 3 backward stepping trials were performed by the uninvolved foot only in a randomized order for each of the 2 task conditions (single and dual task). During the single-task condition, subjects were asked to view an “X” projected at eye level onto a wall 3m in front of them. Subjects were instructed to step as quickly as possible after a distinct tap (shear ground reaction forces greater than 15N and less than 25N) on the heel of the uninvolved foot. Subjects were allowed to practice to become familiar with the test situation and to ensure step clearance of the force platform. After completion of the 6 single-task trials, subjects repeated the protocol under dual-task conditions by performing a modified Stroop test.\(^2\)\(^4\) The modified Stroop test consisted of a 5×5 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 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 it does not address memory, which may be impaired in chronic stroke survivors.

Force platform data were analyzed by code written in Matlab\(^*\)\(^,\)\(^1\)\(^6\)\(^,\)\(^2\)\(^3\) to extract 5 temporal parameters: step initiation, preparation phase, swing phase, foot-off time, and foot-contact time (fig 1). The tap cue was detected as a spike in the shear ground reaction forces in the anteroposterior direction. Step initiation was defined as the first mediolateral deviation of COP toward the swing leg. The step initiation phase was calculated as the time from tap onset to step initiation. Foot-off time was defined by a sudden change in the slope of COP toward the stance foot in the mediolateral direction. Foot-contact time was defined as the onset of unloading in the vertical ground reaction forces. The preparation phase was defined as the time from step initiation to foot off; swing phase was calculated as the time from foot off to foot contact. Each event was averaged across all 6 trials during both conditions for each subject as described in detail elsewhere.\(^2\)\(^3\)

All subjects enrolled onto the study were also assessed by the BBS.\(^2\)\(^5\) In the BBS, the participant is scored on 14 balance tasks graded on a 0 to 4 scale (highest possible score=56/56). Two of the 14 tasks were performed twice (heel/toe stance and standing on 1 foot), once with the involved leg and once with the uninvolved leg; thus, 2 BBS scores were obtained for each chronic stroke survivor (BBS involved and BBS uninvolved).

**Statistical Analysis**

Student t test for independent measures was used to evaluate the influence of left vs right stroke on step reaction times. Wilcoxon signed-rank test and Mann-Whitney U tests were used where the variable was not normally distributed. The effects of stroke and task condition on the mean dependent variables were calculated by a 2-way repeated-measures ANOVA that included group (chronic stroke survivors—controls) as the between-subjects factor with repeated measures on the within-subjects factors of task (single-dual). The dependent variables included the step execution times of the uninvolved foot: (1) initiation phase; (2) foot-off time; (3) foot-contact

<table>
<thead>
<tr>
<th>Table 1: Patient Characteristics</th>
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<tr>
<td>Variables</td>
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<td>N</td>
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<td>Age (y)</td>
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<td>Sex (male/female)</td>
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<td>Years poststroke</td>
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<td>BBS (involved side)</td>
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<td>BBS (uninvolved side)</td>
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<td>Mini-Mental State Examination score</td>
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NOTE: Values are shown as mean ± SD (range) or as otherwise indicated. Abbreviation: NA, not applicable.
RESULTS

Subject Characteristics

Significant differences were seen between chronic stroke survivors (7.3y poststroke) and controls in BBS and Mini-Mental State Examination (47.9±6.1 vs 55.2±1.5 and 26.2±4.7 vs 28.9±1.1, respectively) (see table 1).

Effects of Stroke

There were no significant differences in step reaction times between right vs left stroke; thus, step reaction times for right and left stroke patients were pooled.

There were statistically significant differences across all step execution parameters for both task conditions between chronic stroke survivors and controls (table 2). During the single-task condition, the step initiation phase was 65% longer for the chronic stroke survivors compared with their nonstroke counterparts (279±106ms vs 169±48ms, P=.001). Under the dual-task condition, the step initiation phase was 55% longer for the chronic stroke survivors (403±94ms vs 260±122ms, P=.001). The preparatory phase durations in the chronic stroke survivors were significantly longer during the single task (93%), and only 35% longer in dual-task condition (567±141ms vs 40±79ms, P<.001, and 597±148ms vs 442±110ms, P=.002, respectively). Swing phase durations were 80% longer in chronic stroke survivors during the single-task condition and 46% longer during the dual-task condition (449±218ms vs 305±37ms, P=.018, and 446±141ms vs 305±75ms, P=.001, respectively). Time to foot contact determining the duration of step execution was also significantly slower for chronic stroke survivors in the single-task and dual-task conditions (1295±383ms vs 876±182ms, P<.001, and 1445±249ms vs 1006±258ms, P<.001, respectively).

Effects of the Cognitive Task

In both chronic stroke survivors and controls, the modified Stroop task significantly increased step reaction times (see table 2) compared with the single-task condition. The step initiation phase was 44% longer (from 279±106ms to 403±94ms, P<.001) in chronic stroke survivors and 54% longer (from 169±48ms to 260±122ms, P=.001) for controls. Foot-contact times in chronic stroke survivors increased during the dual-task condition, from 1295±383ms to 1445±249ms, P=.21 (12%) and from 876±182ms to 1006±258ms, P=.004 (15%) in healthy controls. No significant differences were found in preparatory and swing phases in both groups when performing the Stroop task (see table 2).

Additional ANOVAs that included BBS as a covariate were conducted; results showed that foot-contact time (eg, the overall stepping time) remained statistically significant even after

Table 2: Temporal Effects of Modified Stroop Task

<table>
<thead>
<tr>
<th>Step Reaction Times</th>
<th>Stroke Survivors (n = 16)</th>
<th>Healthy Controls (n = 16)</th>
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<tbody>
<tr>
<td></td>
<td>Single Task</td>
<td>Dual Task</td>
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<tr>
<td>Initiation phase</td>
<td></td>
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<tr>
<td>Foot-off time</td>
<td>846±214*</td>
<td>403±94*†</td>
</tr>
<tr>
<td>Foot-off time</td>
<td>846±214*</td>
<td>1445±249*†</td>
</tr>
<tr>
<td>Preparatory phase</td>
<td>567±141*</td>
<td>597±148*</td>
</tr>
<tr>
<td>Swing phase</td>
<td>449±218*</td>
<td>446±139*</td>
</tr>
</tbody>
</table>

NOTE: Voluntary step execution parameters for stroke survivors and healthy controls in both task conditions. Values are means ±1SD in milliseconds.
*Significant differences between stroke patients and healthy controls (P<.05).
†Significant differences between dual- and single-task conditions within groups (P<.05).
including BBS scores as a covariate ($P = .011$), whereas step initiation phase duration did not ($P = .25$).

The following observations were also noted for the stroke patients, and less so for healthy controls. On a few occasions, we had to help chronic stroke survivors to prevent a lateral fall from occurring after forward or backward stepping, especially under dual-task conditions. An additional observation commonly noted in the chronic stroke survivors group during dual-task step execution was halted reading of the colors; whereas controls tended to reduce reading speed while stepping.

A ratio between dual- and single-task test conditions for each phase of the stepping task for the 2 groups was calculated (dual-/single-task ratio, fig 2). A statistically significant increase in the duration of the initiation phase that was of similar magnitude for both groups was found (58% and 50% for chronic stroke survivors and controls, respectively; not statistically different). Fairly similar statistically nonsignificant between-group increases in preparatory-phase (6% and 1%) and swing-phase durations (8% and 2%) were also seen. In addition, $2 \times 2$ ANOVA revealed no significant group-by-task condition interaction for step initiation, preparation phase, and swing phase ($P = .34$, $P = .77$, $P = .93$, respectively).

**DISCUSSION**

The present findings are consistent with other reports demonstrating that performance of an attention-demanding dual task has a destabilizing effect on the postural control of stroke patients during standing\[^3^5\] or walking.\[^3^6\] Here we extend these previous findings to dynamic postural control during the rapid Voluntary Step Execution Test. We demonstrate that chronic stroke survivors had significantly slower stepping times compared with healthy controls; further, performance of a dual task markedly increased stepping times in both groups. Delayed initiation and completion of a voluntary step may well be a marker for increased risk of falling. Biomechanical parameters related to the forces measured at foot contact and to the durations of the phases of the stepping up were correlated with fall.\[^3^8\] Van den Bogert et al\[^3^9\] proposed an inverted pendulum model, which predicted a faster response time as the most important factor for successful balance recovery. Melzer et al\[^1^6\] found that elderly persons with dual-task Voluntary Step Execution Test times of more than 1100ms had 5 times the risk of falling as participants with execution times of less than 1100ms. These findings suggest that falls in stroke patients may result from an inability to preserve balance during self-induced perturbations. Such patients may fail to react appropriately by executing a rapid and effective step response, especially while performing another attention-demanding task.

**Effects of Stroke**

We had asked whether the ability to quickly step during the execution of an attention-demanding task was different between chronic stroke survivors and healthy controls. During the single task, the step initiation phase was 65% (110ms) longer for the chronic stroke survivors compared with the controls. In addition, the preparatory phase was 41% (165ms), the swing phase was 47% (144ms), and foot-contact times were 48% (419ms) longer for the chronic stroke survivors compared with the controls. For the dual-task condition, the corresponding values were 55% (143ms), 35% (155ms), 46% (141ms), and 43% (439ms), respectively (see table 2).

We divided step execution into 3 phases: (1) the step initiation phase, (2) the preparatory phase, and (3) the swing phase. Each of these phases is dominated, although not exclusively, by different physiologic processes. The step initiation phase is mainly dependent on peripheral sensory detection and afferent nerve conduction time, followed by central neural processing and efferent nerve conduction time. During the preparatory phase, the APA are executed (eg, weight transfer), and the actual step is initiated. Finally, the swing phase incorporates the actual motor execution of the task when the leg is lifted and moved to the target location. The duration of the swing phase is mainly dependent on neuromotor mechanisms related to the build-up of muscle force and power to move the leg.

The 60% to 65% between-groups increase in the step initiation phase (in both task conditions) may have resulted from delayed-onset latencies of muscle. Delays in trunk muscles during flexing arm\[^3^0\] and delayed response in the paretic gluteus medius muscle during gait initiation\[^1^4\] have been found previously. It might be a result of slower motor nerve conduction velocities in chronic stroke survivors. However, study results are controversial. Samusik\[^3^2\] and Chokroverty and Medina\[^3^3\] revealed slowing in motor nerve conduction velocities in the affected limbs compared with the unaffected side, whereas Lampl et al\[^3^4\] found no clinical or electrophysiologic evidence for peripheral nerve involvement in stroke patients. Thus, we suggest that the major cause for the delay in the step initiation phase is related to a gradual and general decrease in the speed of information processing, leading to an impairment in initiating motor response observed in stroke patients\[^3^5\] and after unilateral cerebral infarction in rats.\[^3^6\] This modified motor program presumably has to be learned as part of the rehabilitation process.

The 35% to 41% between-groups increase in the preparatory phase duration where APAs are executed may be partly explained by an increase in the time of weight transfer toward the affected leg of stroke patients (eg, which was the weight-bearing leg). Such differences in APA between stroke survivors and healthy controls have been documented.\[^1^0, 3^7\] Kirker et al\[^3^8\] found weak response of the gluteus medius hemiparetic muscle during self-initiated sideways movement before stepping in stroke patients. This may explain longer APAs in chronic stroke survivors in our study. In addition, the time to release co-contraction of antagonistic muscles during standing may act to delay the APA before the actual movement.\[^3^8\] It is also likely that delayed central cognitive processing can

![Fig 2. The interference effect of modified Stroop test in chronic stroke patients and healthy controls (dual-task stepping normalized to single-task stepping). Values represent ratios (percentage ± SD) of the average value of 2 step directions in dual task and the average value of 2 step directions in single task. No significant differences were found between groups.](image-url)
lengthen the duration of the preparation phase; chronic stroke survivors may need more time to plan and execute an APA.30

In chronic stroke survivors, the 47% and 46% increase in swing phase duration during the single and dual tasks, respectively, is most likely a consequence of skeletal muscle weakness in the involved leg. Muscle atrophy and the associated reduction in cross-sectional muscle area of the paretic leg are known to occur in stroke patients.39,40 Consequently, these known effects on muscle morphology and physiology could probably explain most, if not all, of the reduction in swing phase performance seen in the current study in chronic stroke survivors.

Effects of the Cognitive Task

In the current study, we wondered whether an attention-demanding task would delay the execution of a rapid voluntary step compared with the single-task condition. The results illustrate a significant effect of the dual-task test condition on the duration of the step initiation phase in both groups: a 58% increase in chronic stroke survivors and a 50% increase in the controls. This effect is illustrated in figure 2, which shows a ratio between dual- and single-task test conditions for each phase of the task and for the 2 groups. A similar increase in the initiation phase for both groups can clearly be noted. Nonsignificant (see table 2 and fig 2) and fairly similar between-group increases in duration were seen for the preparatory phase and the swing phase. Thus, we conclude that chronic stroke survivors used similar strategies to healthy matched controls during the simultaneous performance of stepping and cognitive task.

This finding is somehow surprising, because we hypothesized that healthy controls would show less interference effects in situations when attention has to be shared between more than 1 task.16 However, the interference effects of attention-demanding task were similar between groups, suggesting that both groups used similar strategies during the simultaneous performance of simple functional and cognitive tasks. It is also possible that chronic stroke survivors focused their attention more strongly on the Voluntary Step Execution Test in the dual-task situation, whereas healthy controls tended to invest their resources in the cognitive task (eg, they tried to perform as well as possible in the Stroop test), because the Voluntary Step Execution Test was not as difficult for them as for the chronic stroke survivors. This potential differential-emphasis behavior might explain the finding that group differences in the Voluntary Step Execution Test did not reach significance when the interference effect of the concurrent attention-demanding task (the average value in dual task normalized to single task the ratio between dual- and single-task test conditions for each task (the average value in dual task normalized to single task) was compared. This explanation is supported by age-comparative laboratory research on cognitive-sensorimotor dual-task situations, which has shown that older participants have larger dual-task–related performance decrements than young adults; they tend to focus their attention more strongly on the sensorimotor task when both tasks are very resource demanding.31-44

Overall, the results from the present study add to a growing body of evidence17-20,26-27,41-44 that shows that central processing factors and attentional capacity are important limitations for balance function during dual-task conditions. In a real-life situation, the amount of time available to execute a step to successfully prevent a fall is short, and any delay in the execution of a step may therefore cause a fall and result in injuries. These results suggest that an additional delay in step execution times under dual-task conditions may be more clinically significant for chronic stroke survivors (eg, 1445ms) because step times were already delayed in single-task condition (eg, 1295ms), well above the threshold that has been cited16 as critical to prevent a fall (1100ms), whereas the additional delay in the control group resulted in a step reaction time that was only 1006ms. Our finding certainly illustrates that chronic stroke survivors may be at considerably greater risk of falling, especially during an attention-demanding task.

Results also showed that foot-contact time remained statistically significantly different between the groups after including BBS scores as a covariate, whereas step initiation time did not. This suggests that step initiation time reflects a dimension of balance control that is similar to that of the BBS procedure, whereas overall stepping time incorporates a dimension of balance function that is not captured with the BBS test.

Although we reviewed a considerable number of intervention studies, we did not find specific interventions to improve stepping speed to facilitate the balance recovery in stroke patients. In one study,47 step training at speed with body weight support was found to be effective in improving self-selected walking velocity. On the other hand, some intervention studies46,47 show improvement in stepping responses in elderly subjects. Furthermore, Silsupadol et al48 found that older adults are able to improve their balance under dual-task conditions only after specific dual-task balance training. All of the above suggest that specific intervention to improve the speed of the stepping response in stroke patients is a recommended area for future research; this may reduce the risk of falls.

Study Limitations

This 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 survivors or to institutionalized stroke survivors. Second is the lack of monitoring falls in stroke survivors. Third, cognitive performance was not assessed in the present study, so we do not know how much of the delay seen in the stroke group is due to an attentional or cognitive deficit. However, we can conclude that the stroke-related deficit in this group of patients affected the different phases of the step execution task similarly—that is, the dual-to-single-task ratios were the same in the healthy group and in the stroke group. Further studies should assess larger sample sizes, should have a prospective design, and should study less healthy or institutionalized stroke populations. Fall follow-up studies are needed to determine whether stepping behavior can predict falls in stroke survivors. The greatest value of these types of studies (ie, case-control) is that they provide preliminary evidence that can be used as the basis for hypotheses in stronger experimental studies.

CONCLUSIONS

Gait and balance impairments and fall-related injuries constitute a serious public health problem in stroke survivors. Speed of voluntary stepping was found to be significantly delayed in chronic stroke survivors, which may lead to an increased risk of falls, especially during concurrent attention-demanding task conditions. The present results suggest that clinical tests of postural function should incorporate dual-task conditions to capture a more complete picture of performance capability of stroke survivors and to provide additional information about the balance control system that is different from that captured with the BBS protocol.

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 Suppliers

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b. SPSS version 10.1, SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.