The Effect of a Cognitive Task on Voluntary Step Execution in Healthy Elderly and Young Individuals

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OBJECTIVES: To investigate voluntary step behavior of healthy elderly individuals during single- and dual-task conditions and to compare it with those of young subjects.
DESIGN: Laboratory-based study.
SETTING: Tests of healthy elderly and young individuals from senior community centers and from the university population in Boston, Massachusetts.
PARTICIPANTS: Sixty-six elderly and 12 young subjects.
MEASUREMENTS: Forward, sideways, and backward rapid voluntary stepping performed as a reaction time task while standing on a force platform and (1) awaiting a cutaneous cue (single task) and (2) awaiting a cutaneous cue while performing an attention-demanding Stroop task (dual task). Step initiation phase, foot-off time, foot contact time, and preparatory and swing phases were extracted from center-of-pressure and ground reaction force data.
RESULTS: Elderly subjects were significantly slower than young in all step parameters under both conditions. For dual compared with single task, the initiation phase increased 108% in the elderly group and 34% in the young. There was a short-term learning effect during the dual task in elderly subjects but not in the young.
CONCLUSION: The disproportional increase in step initiation time during the dual task in the elderly group suggests that they lacked neural processing resources required for swift multitasking during a voluntary postural task. This may be a factor contributing to balance loss and the large number of falls in elderly persons. Training may improve this skill. Clinical tests of postural function should incorporate multitask conditions to capture a more complete assessment of an individual's ability. **J Am Geriatr Soc 52:1255–1262, 2004.**

Key words: aging; balance; falls; postural control; step reaction times

The deterioration of the postural control system with aging can lead to balance impairment with limitations of mobility and severe disability.[1] Falls are the leading cause of injury-related visits to emergency departments and the primary etiology of accidental deaths in persons aged 65 and older;[1] 30% of individuals aged 65 and older and almost 50% of those aged 80 and older experience at least one fall every year.[2] Impaired balance has been correlated with an increased risk for falls and a resulting increase in mortality in those who are prone to falling.[3] The mortality rate for falls increases dramatically with age, and falls are responsible for 70% of accidental deaths in persons aged 75 and older.[1]

The ability to take a quick step or to grasp for external support in the environment are important motor skills that could prevent a fall from occurring. Compensatory strategies, including stepping and grasping, are automatically triggered after different unexpected postural perturbations such as a rapid slip or a trip. A compensatory step provides an enlarged base of support and thus increases the center of mass (COM) displacement that can occur without balance loss.[4] Once a fall is initiated, a rapid step execution is critical for successful balance recovery.[5] Voluntary stepping may also serve an important stabilizing role after low acceleration falls that may occur due to pushes, impacts from swinging doors/elevators, or when standing in a moving vehicle. Furthermore, voluntary stepping may help preserve balance when self-induced falls occur during walking, rising from a chair, or stumbling on a rug or inappropriately placed furniture or telephone cord, situations that may occur in daily life.[6] The majority of falls in the elderly occur during common daily activities, such as walking or changing position[7] or from tripping or tangling of the feet.[8]

Laboratory-based studies of stepping in elderly subjects have mainly been focused on compensatory stepping behavior in a forward direction[4,9] or have been single task in nature, thereby allowing subjects to maintain their cognitive attention on performing the upcoming motor task,[5] but in a real-life situation, the requirement to step commonly occurs under more complicated circumstances with cognitive attention focused on, for example, watching traffic or reading street signs or advertisements and not on performing a specific motor task.[6] Simultaneous performance of

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cognitive and postural tasks has been suggested as a potential contributor to falls in elderly individuals with clinical balance impairments.[10] Most theories on cognitive function conclude that available processing resources are limited.[11] As a result, resource competition may occur during the performance of more than one task, leading to task interference and difficulty in performing motor tasks.[11,12] 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 ensuing injuries.

In the current study, whether an attention-demanding cognitive task would delay the execution of a voluntary step performed in three different directions (forward, sideways, and backward) was examined. In addition, whether the ability to quickly step during the execution of an attention-demanding task was different in a group of healthy young and elderly individuals was examined.

METHODS

Sixty-six healthy elderly volunteers (aged 65–90) and 12 healthy young volunteers (aged 20–39) performed forward, sideways, and backward voluntary steps (Table 1). Subjects were recruited from senior community centers and from the university population. Elderly subjects had to be at least 65 years of age, ambulate independently, score better than 45 on the Berg Balance scale, and have a Mini-Mental State Examination score higher than 24. Individuals with severe focal muscle weakness or paralysis, serious visual impairment, severe peripheral or compression/entrapment neuropathies, any neurological disorders causing balance or motor problems, or cancer (metastatic or under active treatment) were excluded from participation. All subjects received medical clearance from their primary care physician to participate in the study and provided informed consent in accordance with approved procedures by the Boston University Charles River Campus institutional review board.

Experimental Protocol

Subjects were instructed to stand upright and barefoot on a force platform in a standardized stance, their feet abducted 10°, their heels separated mediolaterally by 6 cm,[13] and their hands crossed behind their back. Center of pressure (COP) and ground reaction force data during step execution tests were collected using a Kistler 9287 force platform (Kistler Instrument Corp, Amherst, NY). The force platform data were sampled at a frequency of 100 Hz and stored on a hard disk for later processing.

Eighteen voluntary step execution trials were conducted for each subject, forward, sideways and backward (three trials in each direction always performed in the same order), under two different task conditions preceding the step execution: (1) single task (standing and viewing a target placed on a wall 3 meters away) and (2) dual task (standing and performing a modified Stroop task[14] that was projected at eye level onto a wall 3 meters in front of the subject (100 cm wide by 50 cm high)). The task consisted of reading off colors from a printout showing 25 colored words (five lines of five words), representing color names that were different from the printed colors. For example, the word yellow was printed in red ink. The subjects were instructed to name the colors of the inks, as quickly as possible, until the end of the procedure. The modified Stroop test[14] was used because it requires a considerable amount of focused attention and few instructions to perform. In addition, it requires only direct verbal responses and does not address memory, which may be impaired in the elderly. Subjects were allowed a brief learning period in a sitting position before the start of the experiment. Subjects were instructed to stand evenly on both feet and to step as quickly as possible after a tap cue on the heel of the preferred stepping foot provided manually by the experimenter. This cue may resemble the cutaneous stimulus experienced when the foot hits an object before a stumble or a trip. Average response times were calculated for each of the three step directions.

Data and Statistical Analyses

Specific temporal events were extracted from the step execution data using a program written in MatLab (Math Works Inc, Cambridge, MA). The procedures were similar to those previously described.[15] The following events were extracted from the ground reaction force data (see Figure 1). The tap cue was detected as a spike in the shear ground reaction forces in the anterior-posterior direction. The step initiation was detected as the first mediolateral deviation of the COP toward the swing leg (COP excursion >4 mm away from baseline sway after the tap[15]). Foot-off was defined at the end of the mediolateral shift of the COP toward the stance leg (absolute COP slope <100 mm/s twice in a row). Foot contact was defined as the onset of unloading of the stance leg seen in the vertical ground reaction force as the swing leg contacts the ground (detected unloading of the

Table 1. Group Characteristics

	Old* (n = 66)		Young† (n = 12)	
Characteristic	Mean ± Standard Deviation (Range)			
Age	77.0 ± 6.5	(65–90)	27.0 ± 6.0	(20–39)
Weight, kg	68.0 ± 12.3	(59–101)	65.5 ± 10.0	(54–87)
Height, cm	158.8 ± 8.3	(142–178)	169.4 ± 7.0	(160–183)
Body mass index, kg/m^2	26.9 ± 4.4	(18–40)	22.9 ± 2.2	(20.5–27.5)

* 76% female.

† 75% female.

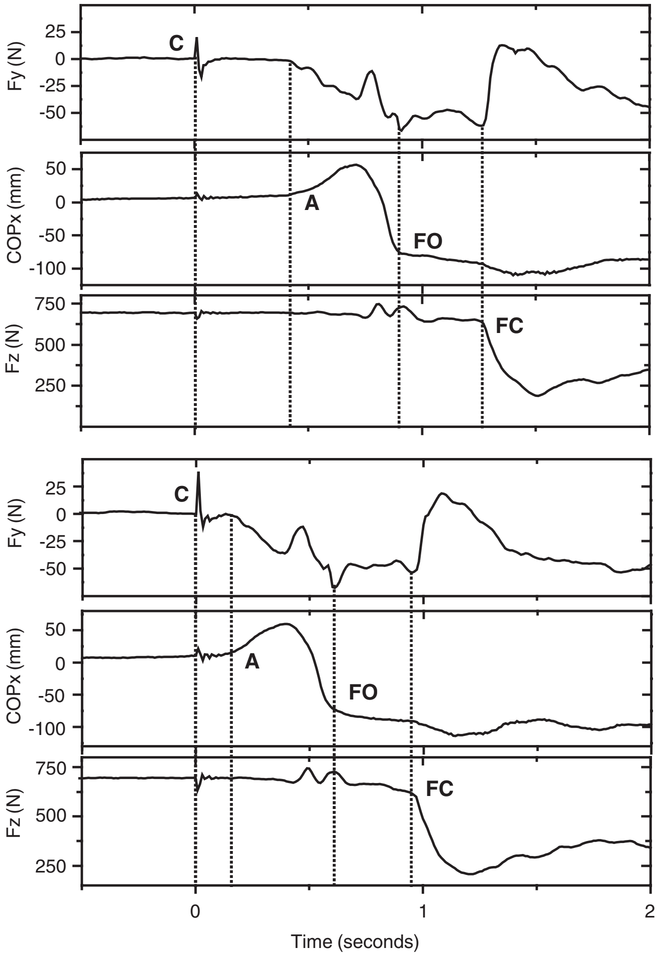

Figure 1. An example of forward step execution data for a 90-year-old subject during single- (bottom) and dual-task conditions (top). Fy = ground reaction forces (shear forces) in anteroposterior direction; Fz = vertical ground reaction forces; COPx = mediolateral center of pressure. The following events are marked with vertical lines; tap cue (C); initial deviation of COPx (A); foot-off (FO); foot contact (FC). The tap cue is detectable in any of the signals. Note the differences in step reaction times between the two task conditions (distance between C and A). See text for further details.

vertical force was faster than 500 Newton/s twice in a row).[16] This event would coincide with loading of the swing leg.[16] Preparatory duration was calculated as the time from step initiation to foot-off.[6] The swing duration was calculated as the time from foot-off to foot contact. Overall step initiation, preparation, and swing phases were calculated from the average values of all three step directions. A total of 1,404 trials from 78 subjects were assessed and analyzed (18 trials from each subject). Of these, 26 trials were excluded because of excessive sway before the tap cue, specific temporal events were not possible to define, or the subject did not initiate a step reaction within 1.5 seconds after the cue signal.

The effects of age, task condition, and step direction on the mean dependent variables (step reaction times) were calculated using SPSS (version 10.1, SPSS Corp., Chicago, IL) using a three-way repeated-measures analysis of variance that included group (young—old) as the between-subject factor, with repeated measures on the within-subject factors of task (single—dual) and three step directions (forward, sideways, and backward). The dependent variables were time to step initiation (initiation phase), time to foot-off, time to foot contact, preparatory phase, and swing phase. A significance level of .05 was used. To analyze the effect of trial order (1–9) on step execution behavior in the two groups of subjects, a linear regression analysis was performed with step number as the independent variable and step initiation time as the dependent variable. The slope of the linear regression line and Pearson correlation coefficient for the association were tested for significance ($P < .05$). Student *t* test for independent measures was used to evaluate the overall effect of the dual task (the average value across all three directions in dual task normalized to single task within each group) on step initiation phase, preparatory phase, and swing phases, between the two age groups. A full Bonferroni correction for uncorrelated measures was used ($P < .017$) for each of the three *t*-tests to achieve an overall significance level of .05.

RESULTS

Effects of Age

There were statistically significant differences across all step execution parameters and step directions for both task conditions between young and elderly individuals (Figure 2). During the single-task condition, step initiation times were 42% to 54% longer for the elderly (65–73 ms across step directions) than for the young individuals. Under the dual-task condition, the differences in step initiation times were substantially larger, with 190% to 256% longer initiation times for the elders (177–312 ms across step directions). The preparatory phase durations during the single task were 39% to 60% longer in the elderly subjects across step directions (114–126 ms). The corresponding values during the dual-task condition were 32% to 72% (108–144 ms). Times to foot contact, determining duration of step execution, were also distinctly different between the two groups. In the single-task condition, average foot contact times for young subjects ranged from 589 ms to 699 ms across the different directions, whereas values for elderly individuals ranged from 853 ms to 992 ms. During the dual-task condition, average foot contact times across the different step directions ranged from 648 ms to 793 ms for the young subjects and from 1,140 ms to 1,336 ms for the elderly subjects. Swing phase durations during the single task were between 29% and 46% (77–111 ms) longer in the elderly subjects across step directions. Corresponding values for the dual-task swing phase durations were 33% to 52% longer in the elderly (87–128 ms). Within the elderly group, there was a weak but statistically significant correlation between age and dual-task step initiation time ($r = 0.33$, $P < .01$), foot-off time ($r = 0.33$, $P < .01$), and foot contact time ($r = 0.29$, $P < .02$). No such association was seen during single-task step execution.

The following observations were also made for the elderly subjects. Under dual-task conditions, 41% of the elderly individuals occasionally did not react at all to the tap cue (between one to four of the nine trials). This also occurred for 5% of the elderly subjects during the single-task

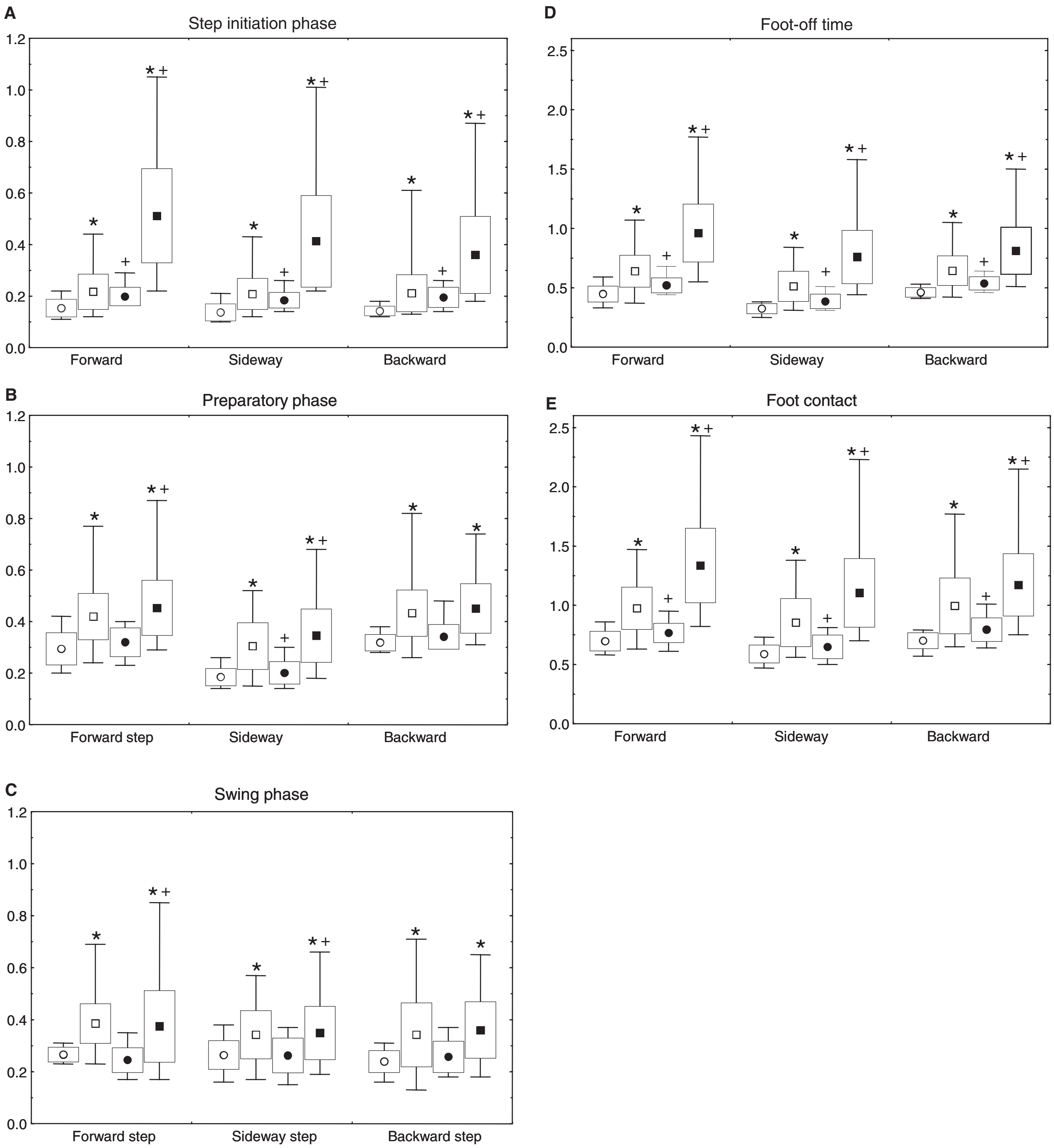

Figure 2. Box plots of voluntary step execution parameters for both groups of subjects and both task conditions for all three step directions. Open symbols represent single-task and filled symbols dual-task conditions. Circles represent young subjects and squares elderly subjects. Placement of symbols indicates mean values in seconds, and vertical limits of the box are ± 1 standard deviation of the mean. The whiskers of each plot indicate minimum and maximum values for each of the parameters. Significant differences *between age groups and †between task conditions within age groups ($P < .05$).

condition. Subjects reported that they felt the tap on their heel but became confused about what to do. A similar observation involved steps in the wrong direction although step direction was known a priori (e.g., sideways instead of backward step). This occurred on occasion for 9% of the subjects under the dual-task conditions but never under the single-task condition. Twenty-four percent of the elderly individuals took an additional lateral step to regain stability after forward or backward reaction time stepping. Such lateral stabilization steps were seen in 15% of the elderly subjects (at least once in nine trials) during single-task conditions and in 19% (at least once in nine trials) during the dual-task condition. In 9% of the subjects, an additional step was taken during both single- and dual-task conditions. None of these behaviors were seen in the young subjects.

Effects of the Cognitive Task

In elderly subjects, the modified Stroop task caused statistically significantly longer step reaction times (Figure 2) than with the single-task condition. During forward stepping, the step initiation time nearly tripled (from 218 ms to 511 ms), whereas during sideways and backward stepping, it approximately doubled (from 208 ms to 446 ms and 211 ms to 372 ms, respectively). Similar increases were found for foot-off and foot contact times (Figure 2). Foot contact times increased from 973 ms to 1,336 ms, 853 ms to 1,140 ms, and from 992 ms to, 1,179 ms between the single- and dual-task conditions for stepping forward, sideways, and backward, respectively. All increases were statistically significant ($P < .05$). The elderly showed a significantly longer preparatory phase during forward and sideways stepping when performing the Stroop task (by 31 ms and 40 ms, respectively, $P < .05$). There was no statistically significant difference in the preparatory phase durations between single- and dual-task conditions during backward stepping ($P = .08$). Swing phase duration in elderly individuals was significantly longer during dual task than single task only for forward stepping (373 ms vs 336 ms), whereas no differences were found for sideways or backward stepping (Figure 2).

Step execution times in young individuals were also significantly delayed during the dual-task condition (Figure 2), although to a lesser extent than in the elderly subjects. Step initiation times increased approximately 50 ms (34%) under the dual-task condition across all step directions (from 134 ms to 153 ms for single task and 184 ms to 199 ms for dual task). Average foot-off times increased from 324 ms to 462 ms for single task to 386 ms to 520 ms across step directions ($P < .05$, Figure 2). Similarly, the time to foot contact was significantly longer during dual-task stepping (648–793 ms, vs 589–699 ms during the single-task condition).

As in the elder group, the preparation phase duration was significantly longer ($P < .05$) under the Stroop task condition when stepping forward (294 ms in single-task vs 321 ms in dual-task condition) but not during sideways (190 ms in the single-task vs 201 ms in the dual-task condition, $P > .05$) or backward stepping (318 ms in the single-task vs 340 ms in the dual-task condition, $P = .09$). No significant differences in the swing phase duration were found between task conditions for any of the three step directions in the young subjects (Figure 2).

Effects of Step Direction/Trial Order

Figure 3 shows separate group averages for each of the three trials for each of the three directions in the order the trials were assessed for single- and dual-task test conditions. In addition, Figure 3 shows the best-fit linear regression line for each of the four testing conditions. Under single-task conditions (Figure 3, top graph), the correlation between trial number and step initiation time for the elderly group was not statistically significant ($r = 0.04$, $P = .3$) and neither was the slope of the regression line. However, in young subjects, there was a weak but significant correlation under the single-task condition ($r = 0.20$, $P < .05$). The slope of the regression line was also statistically significant (slope = 2.9 ms/trial, $P < .05$). Under dual-task conditions for the elderly group (Figure 3, lower graph), there was a statistically significant association between trial number and step initiation time ($r = 0.28$, $P < .001$), with a statistically significant slope of the regression line (slope = 23 ms/trial, $P < .001$). The corresponding relationship in the young group was not statistically significant ($r = 0.10$, $P = .3$).

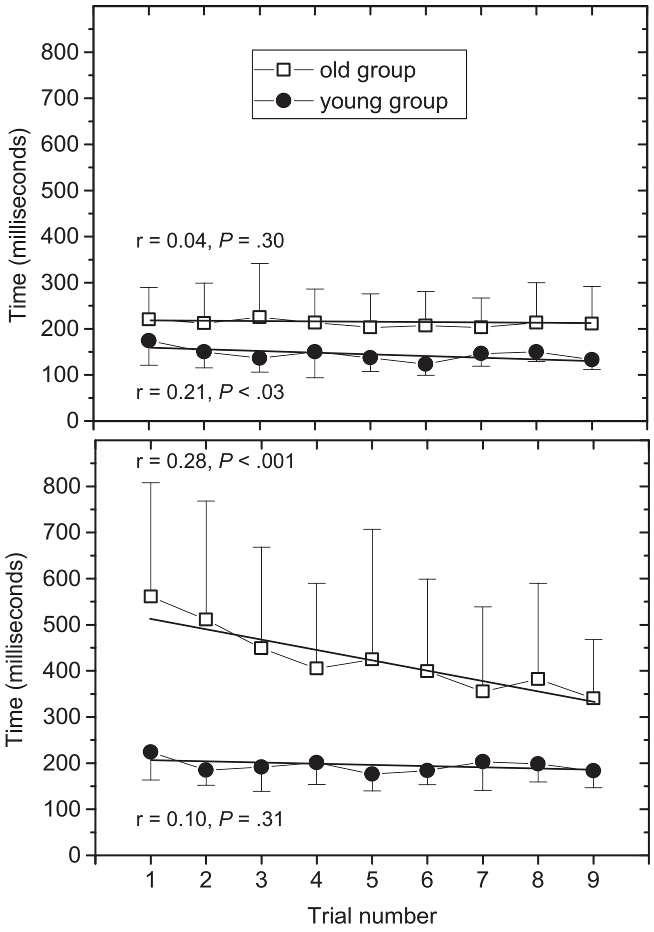

Figure 3. Average step initiation times in milliseconds (open squares represent elderly and filled circles young subject's average ± 1 standard deviation). Nine trials (single-task condition—top; dual-task condition—bottom) presented in the order the tests were assessed to illustrate the short-term learning effect seen in elderly subjects during the dual-task test condition. Trials 1–3 represent forward, 4–6 sideways, and 7–9 backward steps. The lines represent the best-fit linear regression line.

DISCUSSION

A quick step execution, whether it is compensatory in nature and triggered by a perturbation[17–19] or voluntary, is an important skill that can serve to alter the base of support, preserve stability, and prevent a fall. A delayed initiation and completion of a voluntary step may well be a marker of increased risk of falling. Using an inverted pendulum model, one study[20] predicted that a faster response time would be the most important factor for successful balance recovery. Furthermore, using an optimal control model of compensatory stepping, another study[16] claimed that, to prevent the COM from falling beyond the stability margins, a step must be completed within approximately 1,100 ms.

Effects of the Cognitive Task

The current study examined whether an attention-demanding cognitive task would delay the execution of a voluntary step more than with the single-task condition of only performing the step. The results illustrate a statistically significant effect of the dual-task test condition on the duration of the step initiation phase, in both elderly (108% increase vs the single task) and young subjects (34%).

Figure 4 shows the ratio between dual- and single-task test conditions for each phase of the stepping task for the two groups. A disproportionate and statistically significant increase in the initiation phase for the elderly group can be clearly seen. Smaller and fairly similar statistically nonsignificant between-group increases in duration were seen for the preparatory phase and the swing phase (5–10%).

The voluntary step execution task had been divided into three phases: the step initiation phase, the preparatory phase, and the swing phase. Different physiological processes dominate each of these phases, although not exclusively. The duration of 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, anticipatory postural adjustments are executed, and the actual step is initiated. Finally, the swing phase incorporates the actual motor execution of the task when the leg is lifted and physically moves 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 execute the task of taking the step.

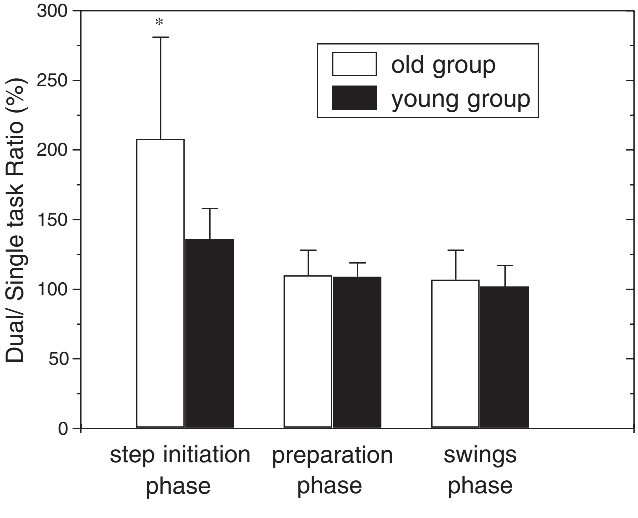

Figure 4. The interference effect of modified Stroop test in elderly and young subjects (dual-task stepping normalized to single-task stepping). The values represent ratios in percentages ± 1 standard deviation of the average value of all three directions in dual task/the average value of all three directions in single task. *Significant differences between age groups (old vs young) ($P < .017$).

Because sensory detection thresholds and nerve conduction velocities were similar between the two task conditions, it appears that the increase in duration of the step initiation phase during the dual task was largely due to an increase in central neural processing time. Similar influence of attention-demanding tasks on postural control has been demonstrated in previous studies. A recent study[21] found that, in frail elderly subjects, a dual-task condition provoked a slower gait with an increased number of steps, a reduction in cadence and step length, and a significant increase in the number of lateral deviations and stops. Other studies have reported that balance-impaired elders who perform a cognitive task show a reduction in postural performance during quiet stance[22,23] as well as walking.[6,24,25] Furthermore, the ability to recover balance after a perturbation requires more attentional resources in healthy elderly than in young subjects.[26] One study[27] found that the response latency and amplitude of agonist and antagonist muscles were slower and smaller when a cognitive task was performed simultaneously with a platform perturbation, suggesting that, with increasing age, the execution of a motor task requires increased attention.

Consequently, the results from the present study add to a growing body of evidence[10,21–29] showing that central processing factors and attentional capacity are important limitations for postural reactions. During the single-task condition, the elderly individuals executed a step in less than 1 second. Under the dual-task condition, the execution was delayed by about 300 ms, bringing the duration above the 1,100 ms threshold that has been sited as critical to prevent a fall from occurring after a balance perturbation.[16] Although the subjects executed a voluntary step, making a direct comparison with a model simulation for compensatory stepping difficult, it certainly illustrates that, during an attention-demanding task, even healthy elderly individuals may be at considerably greater risk of falling.

Effects of Age

Whether the ability to quickly step during the execution of an attention-demanding task was different between healthy elderly and young individuals was also examined. Considering that the subjects were healthy with no known balance problems or neurological/motor deficits, the large age-related effects were surprising. The elderly subjects were significantly slower than the young ones in all step parameters under single- and dual-task conditions. During the single task, the step initiation phase was on average across all step directions 48% longer (69 ms), the preparatory phase 46% longer (118 ms), and the swing phase 37% longer (91 ms) for the elderly group than for the young. For the dual task, the corresponding values were 130% (250 ms), 48% (127 ms), and 42% (105 ms). Similar results have been identified for other reaction time paradigms,[30] including step initiation (reaction) time and preparation (weight transfer) time.[31–33]

There are a range of physiological factors that may be involved in these age-related changes, including decreased nerve conduction velocity, increased sensory detection thresholds, increased central processing time, increased passive tissue stiffness, increased active muscle stiffness due to coactivation or initial postural set, increased reliance on vision for postural control/reassurance, and decreased muscle force and power generation capacity. A progressive decrease with aging in nerve conduction velocity is well established,[34,35] with a reported decrease of 10% to 15% for subjects between 30 and 75 years of age.[35] Consequently, a decrease in nerve conduction velocity can only explain 15% of the delay in step initiation in the elderly subjects, suggesting that the major cause for the 48% and 130% delays in single and dual tasks, respectively, is related to a reduced central processing capability[36] and increased sensory detection thresholds. Errors in step direction and nonresponses noted in the elderly subjects mainly during dual-task step execution, as well as mixing up the colors and reduced reading speed or even halted reading of the colors during the Stroop task, would support such an interpretation.

An increase in passive tissue stiffness present in elderly subjects may partly explain the nearly 50% increase between age groups in the preparatory phase duration, during which associated postural adjustments are executed.[37] In addition, the time to release coactivation of antagonistic muscles[38] may act to delay the adjustment of the body COM before the actual movement. It is also likely that delayed central cognitive processing can cause an increase in the preparation phase duration, during which elders may need more time to plan an anticipatory control strategy, a finding supported by recent studies.[28,29]

The 37% and 42% increases in swing phase duration during the single and dual tasks, respectively, is most likely a consequence of sarcopenia and the associated reduction in cross-sectional area and force-generating capacity, including possible defects in contractile proteins known to occur with old age.[39,40] A reduction in muscle mass with increasing age, due to loss and decrease in fiber size, especially type II fibers,[41,42] will lead to a loss of muscle power.[43] One study[44] found that peak and mean power output in the elderly were 46% and 36% lower, respectively, than in the young. Another study[45] found that maximum isokinetic torques developed by the old were 20% to 40% lower than those of young adults, especially at high velocities. Consequently, known age effects on muscle morphology and physiology could explain most if not all of the reduction in swing phase performance seen in the current study in the elderly subjects.

Effects of Step Direction and Trial Order

As seen in Figure 3, under the dual-task condition for the elderly subjects there was a gradual improvement in step initiation time across the nine trials, noted as a statistically significant negative slope and correlation coefficient. In a separate study, the same effect was found when the step direction was randomized (unpublished data), suggesting that the gradually faster response was an effect of short-term learning or improved task familiarity during the test session and not related to step direction per se. The learning effect was not present in the young group, probably because the task was less difficult to perform for these subjects or because additional subjects would be needed to detect the smaller effect seen in the young subjects (Figure 3). There was a small but statistically significant learning effect during the single task in the young subjects, where the variability was smaller than for the dual task (Figure 3). Overall, these results indicate that there is an ability of healthy elderly subjects to improve dual-task performance in response to training. The improvement of the step initiation phase was probably due to a short-term improvement in central processing speed. This interpretation is consistent with experimental studies in animals and humans that have shown that training to perform specific limb movements may result in a reorganization of the cortical motor area.[46,47] The motor cortex representation of a specific task can reorganize rapidly in response to training or even during actual motor practice.[48]

In summary, a concurrent attention-demanding task can significantly delay voluntary balance responses in elderly individuals, which may lead to an increased risk of falls and ensuing injuries. These results indicate that rapid voluntary stepping during a dual-task condition is more taxing for the available cognitive resources in healthy elderly subjects than in young subjects. Finally, if the ability to rapidly execute a step during a cognitive task is a skill that can be improved by training, as the present study suggests, such tasks should be an important component of balance rehabilitation programs for elderly individuals. In addition, it suggests that clinical tests of postural function should incorporate dual-task conditions to capture a more complete picture of an individual's performance capability. A step execution test, similar to the one used here, could be a simple, safe, and inexpensive test to detect severity of balance impairments in the clinic and identify elders who are at risk of falling.

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