Cognitive Influence on Postural Stability: A Neuromuscular Analysis in Young and Older Adults

Julie K. Rankin, Marjorie H. Woollacott, Anne Shumway-Cook, and Lesley A. Brown

As our population ages, a stronger interest in the issue of balance control has emerged. Previous research has shown that postural stability declines with age, and that these declines may be due to a multitude of factors that increase the likelihood of serious falls in many older adults. Included among these is an age-related deterioration in the three sensory systems contributing to postural control (somatosensory, vestibular, and visual system). There is a marked decline in vibratory sensation (1), number of vestibular hair cells (2), and visual acuity (3). On the output side, there is age-related slowing of peripheral nerve conduction velocity, a reduction in the number of motor units, and a reduction of muscle mass (4–6). Finally, central processing abilities also decrease with age, as seen by a reduction in the speed with which older people can react and move (7). The prevalence of serious falls in the older adult population has stimulated the search for a better understanding of the mechanisms of balance control and the effects of aging on these mechanisms.

Traditionally, postural control is considered to be automatic and thus independent of cognitive processing (8–13). However, a number of studies have begun to question this assumption (14–19). Kerr and colleagues (14) questioned this concept and proposed that cognitive spatial processing and postural regulation may require common mechanisms. This experiment showed that maintaining a difficult posture during the presentation of memory items affected recall for a spatial memory but not a verbal memory task. The results implied that cognitive spatial processing relies on neural mechanisms that are also necessary for the regulation of standing posture, suggesting that cognitive processing influences balance ability.

Teasdale and colleagues (20) tested the ability of young and older adult subjects to remain in an upright posture under changing visual and surface conditions, while simultaneously performing a reaction-time task. The reaction-time task involved the subjects’ pressing a button when an auditory cue was randomly presented as the subjects were standing. Results demonstrated that a decrease in available sensory information significantly disturbed the young and the older adults’ ability to maintain balance. It was concluded that with this decrease in sensory information, the postural task required an additional allocation of attentional resources for older adults.

Previous research in our laboratory (21) has demonstrated that recovery of postural stability following a surface perturbation is attentionally demanding and that attentional demands are greater in older adults than in young adults. In
addition, results found that older adults favor stepping as a fall prevention strategy, and, in a dual-task situation, they take a step before the center of mass (COM) exceeds the base of support. The finding that older adults step more frequently than young adults in response to threats to balance is particularly surprising in light of the finding that stepping was found to be more attentionally demanding than feet in place strategies.

Why do older adults step more frequently in multitask conditions? It is possible that changes in attentional demands in the dual-task condition affect the spatial and/or temporal characteristics of the feet-in-place strategy, making it less effective for postural recovery and thus necessitating a switch to a stepping strategy. It could be hypothesized that recovery is made less effective because of either a reduction in muscle response amplitude or, alternatively, a slowing in muscle response latency. In this current study we examine task-specific changes in neuromotor response characteristics (both the time of onset of muscle activity and the amplitude of muscle response) of balance control during attentionally demanding tasks in young versus older adults to test these alternative hypotheses. We hypothesized that these changes in neuromuscular response characteristics would be more pronounced in older than in young adults.

**Methods**

**Apparatus**

This experiment made use of a hydraulically activated movable platform system that moved either forward or backward. The amplitude of movement was 15 cm, and the movement velocities ranged from 20 to 60 cm/s. For each trial, video recordings of all subjects were made.

Electromyography (EMG) was used to evaluate the spatial and the temporal characteristics of neuromuscular responses to the perturbation conditions. Bipolar surface electrodes (DE-02, Delysys, Inc., Massachusetts) were placed on the skin area over the gastrocnemius (GA), tibialis anterior (TA), biceps femoris, rectus femoris, erector spinae, and rectus abdominus muscles to determine EMG activity. EMG onsets were determined by visual inspection of the recorded electromyographic response. Onset was considered as the point when the signal rose greater than three standard deviations (SDs) from the baseline level of activity. For each subject, integrated EMG (IEMG) values were obtained by integration of the linear envelope (full-wave-rectified and low-pass-filtered [40-Hz] signal) over a window from 36 to 500 milliseconds following perturbation onset. The integrated output was then divided by the time at designated integration bins of 36–70, 70–150, 150–350, and 350–500 milliseconds.

These bins were selected to reflect the neuromuscular responses at monosynaptic (36–70 milliseconds) and at supraspinal processing levels (70–500 milliseconds). We subdivided the latencies from 70 to 500 milliseconds into three bins, as it was a long time interval and would allow us to determine if there were differences in the effect of the cognitive task on postural responses according to time after perturbation onset. To facilitate between-group comparisons of the IEMG, the IEMG that was gathered 100 milliseconds before the platform perturbation was subtracted from the IEMG that was activated by the perturbation.

**Protocol**

Subjects were asked to perform a subtraction task before and while recovering from an external disturbance to balance. The subtraction task required the subjects to subtract by threes from a randomly assigned number greater than 100. A different starting number was given in each math trial. The subjects performed the math task before the onset of data collection and continued until they were instructed to stop. Instructions were given to count as quickly and as accurately as possible and to continue counting through the plate movement. To analyze the subjects’ performance on the math subtraction task, their verbalizations were recorded from the microphone headset.

**Perturbation Protocol**

Subjects were instructed to stand barefoot on a movable platform, look straight ahead with their arms crossed and feet shoulder width apart, and to try to maintain their balance throughout the experiment without taking a step (Figure 1). To prevent falling or injuries, the subjects wore a safety harness, and a spotter was provided to offer support if needed.

The perturbation velocity for young adults ranged from 20 to 70 cm/s and for older adults from 15 to 60 cm/s. Smaller perturbations were included for older adults because they had smaller stability limits than young adults. For purposes of comparative evaluation between the young and the older adults, only the common perturbation velocities were used in this study (20, 30, 40, 50, 60 cm/s). Table 1 shows the trial numbers corresponding to the various perturbation conditions. Because ankle strategies are seen at the lower-velocity perturbations, the criterion for analysis...
was set at platform translations of 15 cm at 20 cm/s and 15 cm at 30 cm/s for both the young and the older adults (22). Catch trials were randomly elicited to minimize anticipation effects. These catch trials consisted of forward directed perturbations (15 cm/s) as well as control trials in which the plate did not move. Practice trials were given to reduce any confounds created by the subjects’ learning a new skill.

Subjects were exposed to 6 trials at each perturbation condition in a randomized design for a total of 48 trials. The verbal subtraction task was performed in half of the trials. The data were collected over an 8-second interval. The plate movement was programmed to trigger at 4 seconds from the start of data collection in each trial.

A limitation of this study was the small number of subjects performing an ankle strategy. Because of a moderate starting perturbation size of 15 cm at 20 cm/s, the number of older participants using the ankle strategy was limited. However, statistically, using 13 subjects for IEMG magnitude comparisons was enough for this study to achieve a power of 80% at an alpha of .05. Previous research by Lin and Woollacott (unpublished data, 1997) evaluated postural response characteristics of stable and unstable adults by using lower perturbation velocities with amplitudes of 5, 10, and 15 cm and five velocities of 10, 20, 40, 60, and 80 cm/s. It is believed that starting the perturbations at lower amplitudes and velocities would have increased the subject pool performing an ankle strategy.

Statistical Analysis

The EMGs were analyzed using a multivariate approach to account for the correlation of responses within each of the respective bins. A two-factor design was employed. Two levels of both age (young and old) and math (math/no math) were crossed to create a $2 \times 2$ multivariate analysis of variance.

To compare similar responses across subjects and across young and older adults, only those subjects who exhibited responses characterized by movement predominantly at the ankle (an ankle strategy) were evaluated. The ankle strategy was defined quantitatively by the degree of hip flexion determined from the kinematic data obtained from a companion study by Brown and colleagues (21). The amount of hip flexion was calculated and the quartile scores for the range obtained. The amount of hip flexion ranged between 3.13° and 83.27°, with quartile scores of 13° for the lower quartile and 26° for upper quartiles. The ankle strategy was considered to occur in all behavioral responses with minimal hip flexion. The feet-in-place responses having less than the lower quartile limit of 13° were labeled as ankle strategies; everything above the upper quartile of 26° was considered to be a hip strategy. The quantitative values were visually verified by viewing of the video recording of the experimental sessions. When the subject demonstrated a starting posture with spinal hyperextension, an ankle strategy was then defined visually as the body rotating around the ankle joint with minimal hip or knee movement.

Subject Selection

Twenty-six healthy adults volunteered to participate in the study. Of these 26, there were 14 healthy young adults (21–36 years; $M = 25.3, SD = 5.2$ years) and 12 healthy older subjects (aged 68–87 years; $M = 78.7, SD = 5.0$ years). In all cases the adults had had no more than two falls within the previous 6 months. All participants self-reported and received medical clearance from their personal physician stating that they were free from uncontrolled cardiovascular disorders and diabetes mellitus. Physical examinations performed by a physical therapist and a board-certified neurologist revealed no musculoskeletal, cognitive, or neurological disorders. All subjects were informed of the testing procedures before they signed a consent form.

As mentioned in the preceding subsection, only data from subjects who used the ankle strategy were selected for data analysis. Subjects who used the ankle strategy included six older adults with an age range from 74 to 87 years ($M = 79.33$ years, $SD = 4.46$ years) and seven younger adults with an age range from 20 to 36 years ($M = 24.29$ years, $SD = 5.53$ years). The sample size of 13 subjects was chosen to

### Table 1. Perturbation Conditions for Young and Older Adults

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Condition</th>
<th>Trial</th>
<th>Platform Velocity, cm/s</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Adults</td>
<td>1. No Math/ Math</td>
<td>4.26,32 / 2.18,27</td>
<td>20</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>2. No Math/ Math</td>
<td>3.36,47 / 11.43,48</td>
<td>30</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>3. No Math/ Math</td>
<td>7.15,30 / 1.9,29</td>
<td>40</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>4. No Math/ Math</td>
<td>21.28,39 / 6.23,33</td>
<td>50</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>5. No Math/ Math</td>
<td>14.25,37 / 8.19,35</td>
<td>60</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>6. No Math/ Math</td>
<td>12.40,45 / 2.44,46</td>
<td>70</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>7. Control</td>
<td>1.5,9,14,17,22,24,34,38,41,42</td>
<td>0</td>
<td>No Movement</td>
</tr>
<tr>
<td></td>
<td>8. Catch</td>
<td>10.16,31 / 13.20,42</td>
<td>15</td>
<td>Forward</td>
</tr>
<tr>
<td>Older Adults</td>
<td>1. No Math/ Math</td>
<td>4.26,32 / 2.18,27</td>
<td>15</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>2. No Math/ Math</td>
<td>3.36,47 / 11.43,48</td>
<td>20</td>
<td>Backward</td>
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<td>15</td>
<td>Forward</td>
</tr>
</tbody>
</table>
achieve a power of 80% at an alpha of .05 for IEMG magnitude comparisons.

**Results**

To test the hypothesis that increased attentional demands affect either amplitude or onset latency of in-place muscle responses, we compared onset latency and IEMG magnitudes during postural recovery in isolation (control condition) versus during the simultaneous performance of the secondary cognitive task (experimental condition).

Tables 2 and 3 compare onset latency for the GA and the TA muscle groups in the control (balance alone) and experimental (balance and math task) conditions for young versus older adults. Only onset latencies between 70 and 200 milliseconds were used to exclude monosynaptic responses (40–70 milliseconds) and voluntary responses (over 200 milliseconds) (23). In both control and experimental conditions, onset latencies for GA and TA were significantly longer in the older adults compared with those for younger adults (for GA, F[1,145] = 13.19, p = .0004, and for TA, F[1,140] = 30.05, p = .0001). However, there was no task by latency effect in the GA or the TA for either age group (GA, F[1,145] = 1.38, p = .222; TA, F[1,140] = 0.03, p = .8611). There was also no age by task interaction for the GA or the TA muscle groups (GA, F[1,145] = 0.04, p = .8443; TA, F[1,140] = 0.48, p = .4889). Thus there was no significant effect of attentional load on onset latency of GA or TA muscle responses in either group. In contrast, muscle response amplitude was affected by attentional load.

When data for young and older adults were considered together, a math effect was seen in the EMG interval of 350–500 milliseconds for the GA muscle (F[1,38] = 22.2, p = .0001) (no significant math effect was seen before 350 milliseconds). Figure 2 illustrates this overall math effect when both the young and the older adult subjects are collapsed together. Note that the EMG magnitude is smaller for older adult subjects. Figure 5 illustrates the individual subjects’ values for the percentage of difference in IEMG activity in the math and the no-math conditions were calculated for both young and older adult subjects. Figure 5 illustrates the individual subjects’ values for the percentage of difference in IEMG activity of the GA between the math and the no-math conditions for the bin interval of 350–500 milliseconds. Note that, as a group, the older adults show a large decrease in GA amplitude for the math conditions, whereas the young adults do not. By contrast, there was no significant difference in age by math interaction for the TA.

The second hypothesis to be tested was that these effects would be more pronounced in older versus young adults. When data for young and older adults were compared, a math by age interaction was seen in the GA EMG at the time interval of 350–500 milliseconds (F[1,38] = 6.05, p = .0186). To illustrate the age by math interaction, the percentages of difference in the IEMG activity in the math and the no-math conditions were calculated for both young and older adult subjects. Figure 5 illustrates the individual subjects’ values for the percentage of difference in IEMG activity of the GA between the math and the no-math conditions for the bin interval of 350–500 milliseconds. Note that, as a group, the older adults show a large decrease in GA amplitude for the math conditions, whereas the young adults do not. By contrast, there was no significant difference in age by math interaction for the TA.

**Table 2. Onset Latencies of the GA for the Control (Balance Alone) and Experimental (Balance and Math) Conditions**

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Balance Only (Mean), ms</th>
<th>Balance Only (SD), ms</th>
<th>Cognitive and Balance Tasks (Mean), ms</th>
<th>Cognitive and Balance Tasks (SD), ms</th>
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</thead>
<tbody>
<tr>
<td>Young Adult</td>
<td>104</td>
<td>16</td>
<td>107</td>
<td>23</td>
</tr>
<tr>
<td>Older Adult</td>
<td>116</td>
<td>15</td>
<td>118</td>
<td>16</td>
</tr>
</tbody>
</table>

**Notes:** GA = gastrocnemius; SD = standard deviation.

**Table 3. Onset Latencies of the TA for the Control (Balance Alone) and Experimental (Balance and Math) Conditions**

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Balance Only (Mean), ms</th>
<th>Balance Only (SD), ms</th>
<th>Cognitive and Balance Tasks (Mean), ms</th>
<th>Cognitive and Balance Tasks (SD), ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Adult</td>
<td>123</td>
<td>29</td>
<td>121</td>
<td>26</td>
</tr>
<tr>
<td>Older Adult</td>
<td>144</td>
<td>31</td>
<td>149</td>
<td>21</td>
</tr>
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</table>

**Notes:** TA = tibialis anterior; SD = standard deviation.

Figures 4A and 4B offer a presentation of the EMG data recorded from typical young and older adult subjects as a comparative view of the average absolute IEMG magnitude of the GA and the TA in response to the math versus no-math condition. Note that there appears to be a reduction in muscle response amplitude in both the agonist (GA) muscle between the time interval of 350–500 milliseconds and antagonist (TA) muscle group between the 150- and 500-millisecond time interval when the cognitive math task is performed.

The second hypothesis to be tested was that these effects would be more pronounced in older versus young adults. When data for young and older adults were compared, a math by age interaction was seen in the GA EMG at the time interval of 350–500 milliseconds (F[1,38] = 6.05, p = .0186). To illustrate the age by math interaction, the percentages of difference in the IEMG activity in the math and the no-math conditions were calculated for both young and older adult subjects. Figure 5 illustrates the individual subjects’ values for the percentage of difference in IEMG activity of the GA between the math and the no-math conditions for the bin interval of 350–500 milliseconds. Note that, as a group, the older adults show a large decrease in GA amplitude for the math conditions, whereas the young adults do not. By contrast, there was no significant difference in age by math interaction for the TA.

GA muscle EMG tracings from two representative younger and older adult subjects are shown in Figure 4A.
As seen in Figure 4A, data from subject O5 represent typical muscle responses of the older adult group in the 350–500-millisecond interval, showing a decline in GA muscle activity during the math task. The mixed results of the younger adults are shown in Figure 4A, which demonstrates a lack of any specific trends in the GA muscle’s EMG activity from the no-math versus math condition during this time interval.

Figure 4B offers a comparative view of each subject’s average TA IEMG magnitude within the young and the older adult groups in response to the math versus no-math condition for the time interval of 150–350 and 350–500 milliseconds, respectively. Again a math effect was seen but no age by math interaction.

**DISCUSSION**

Maintaining balance is a complex process involving sensory detection of postural changes, integration of sensorimotor information within the central nervous system, and execution of appropriate musculoskeletal responses. Loss of balance implies that the system failed in some respect. One possible cause for failure could be a deficit in the higher brain center’s ability to allocate appropriately the attentional resources necessary for postural stability.

The purpose of this study was to determine the effect of attentional demand on the spatial and the temporal characteristics of the neuromotor response to loss of balance. This was achieved by examination of the neuromuscular responses elicited by a balance disturbance when a cognitively difficult (math) task was performed versus a control (no-math) condition. It was hypothesized that a decrease in attention to balance recovery would be observed in both young and older adults when they were performing the secondary cognitive task. The interference in cognitive processing would be characterized as either a reduction in muscle amplitude or onset latency.

Results of the study showed there was a decrease in muscle response amplitude in both the agonist (GA) and antagonist (TA) muscles when subjects were performing the cognitive math task. This decline of muscle activity when subjects were performing the secondary cognitive task suggests that less attentional space was available for balance control.

According to Schmidt (24), if two tasks can be performed simultaneously as well as individually, then at least one of them does not require attention or a portion of the limited capacity. On the other hand, if one task is performed less well in combination with some other task, then both are thought to require attention. Thus attention is defined in terms of whether or not activities interfere with each other.

It was demonstrated in this study that an overlap of the math task with the balance task was evident by the reduced muscle activity when the math task was performed. This indicates that interference did occur between the two tasks, suggesting that balance requires attentional resources.

Results from this study support the results from a previous companion study in our laboratory by Brown and colleagues (21) that recovery of balance is attentionally demanding. In addition, results from the current study suggest that the preference toward stepping found in the study by Brown and colleagues of older adults (21) is not the result of changes in onset latency, but may be due to a reduction in muscle amplitude in the initial postural response. We suggest that, in a dual-task condition, deficient muscle recruitment (as seen by reduced EMG activity) results in the selection of an alternate response strategy, the stepping strategy, to ensure the success of balance recovery.

The second question to be pursued was whether the older population would demonstrate a greater decrease in muscle amplitude than the younger when performing the cognitively demanding secondary task. The result of the comparative analysis of GA muscle activity between the younger and the older adults showed that there was a significant age by math interaction during the time interval of 350–500 milliseconds. This time interval indicates that the decline in muscle response is occurring at a supraspinal versus monosynaptic (reflexive) level. It was not surprising that attentional interference was seen at the time periods associated with supraspinal processing because this would be the level...
at which cognitive influences would dominate. One might expect the IEMG data to show a math effect at the 150–350 ms range, because voluntary reaction time experiments by Henry and Rogers (25) and Klapp and Erwin (26) have shown cognitive control as early as 159 ms (24). This was the case for the TA muscle. However, our data showed this effect during the 350–500-millisecond interval for the GA muscle. This interval is well within the window of time in
which automatic postural responses are used to stabilize the body. For example, center-of-pressure data typically indicate that balance is not stabilized for at least 1 second after the beginning of a perturbation (S-I. Lin and M.H. Woollacott, unpublished data, 1997).

When data from the young and older adults were combined, a decrease in muscle activity was seen during the cognitive task. However, the older adults’ deficit was significantly larger than that of the young adults. This suggests that older adults have more interference when performing the dual task.

It is interesting that reductions in muscle response amplitude in both agonist and antagonist muscles were observed. In the older adults the reduction of activity in both agonist and antagonist muscles would reduce active force input and require the participants to rely more on passive viscoelastic properties of the musculoskeletal system than on active control when responding to a balance threat.

In young adults reductions were limited to the antagonist muscles in the majority of participants and agonist (GA) responses were reduced minimally. This is a more efficient outcome than that seen in the older adults, as the agonist muscle (GA) serves to return the center of mass to its resting position and thus is the prime mover.

The findings from this study may serve as a basis for the development and the implementation of new balance retraining programs to improve stability with the use of multiple tasks. Typically therapeutic programs for balance control focused on a single-task protocol. This study offers support for a balance training program that involves a protocol beginning with single tasks and moving to multitasks that progress in difficulty. This multitask training program may be an appropriate intervention choice for the improvements of postural control in specific subpopulations of patients and older adults with balance impairments. The goal of this multitask training program would be to reestablish or increase the efficiency of synaptic pathways to allocate adequate attention to balance tasks, even when secondary cognitive tasks are being performed.

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<tr>
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<td>September 5–29</td>
</tr>
<tr>
<td>Clinical Teaching</td>
<td>October 2–27</td>
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