Frontal Plane Instability Following Rapid Voluntary Stepping: Effects of Age and a Concurrent Cognitive Task

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Background. Quick step execution may prevent falls when balance is lost. Lateral steps often emerge as a consequence of frontal plane instability arising after the first rapid step. In this study, we suggest a new analysis, focusing on the variability of the frontal plane fluctuations of center of pressure (CoP), that is, mediolateral instability, and their changes over time during and immediately following rapid voluntary stepping in older and younger adults in single- and dual-task conditions. This may be useful in understanding age-related alterations in the locomotor control system.

Methods. Seventeen older adults, who live independently in the community, and 16 younger adults performed rapid forward voluntary stepping under single- and dual-task conditions. The average mediolateral CoP fluctuations, that is, the average distance the CoP travels from side to side in the frontal plane over time, standard deviation, and the coefficient of variation of mediolateral CoP fluctuation were extracted and calculated from CoP data during and immediately following rapid voluntary stepping using a force plate.

Results. We found an age-related increase in the coefficient of variation that represents the variability of frontal plane fluctuations and no significant differences in the average and standard deviations of frontal plane fluctuations. Cognitive task had no influence on measures of frontal plane fluctuations in both age groups.

Conclusion. The study showed frontal plane instability during and immediately following rapid stepping in older persons. This may be a factor contributing to lateral balance loss and the large number of lateral falls seen in the older population.

Key Words: Aging—Balance—Falls—Postural control—Variability.

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Balance control is the foundation of our ability to move independently and safely. It is defined as the ability to maintain one’s center of mass (CoM) within his center of support and by that remain stable and refrain from falling (1). Deterioration of balance control associated with aging can lead to balance impairment, mobility restriction, falls, and eventually severe disability. Thirty percent of individuals older than 65 years, and almost 50% of those older than 80 years, experience at least one fall every year (2). Hektoen and colleagues (3) found that 40%–60% of the falls result in injuries that require medical attention and hospital admissions. Falls are the leading cause of accidental death in older adults (2), with more than 90% of hip fractures occurring as a result of falls (4). One fourth of older people who sustain a hip fracture die within 6 months of the injury (5).

Control of frontal plane stability appears to be a major variable that is associated with falling (6); it is crucial in preventing lateral falls, which encompass many falls and may cause hip and pelvic fractures in noninstitutionalized older persons (7). Quantitative studies of quiet standing that typically focused on properties of sway found impaired ability to control balance in the frontal plane in older adults. Participants with a history of falls showed increased mediolateral (ML) spontaneous sway in a near-tandem stability test with eyes open and closed (8,9) and during narrow base standing (10,11). Furthermore, prospective studies showed that increased ML spontaneous sway (ML-CoP excursions) was the best predictor of future falls (12,13).

Also, stepping reactions, whether they are compensatory or voluntary, have been found to be associated with increased risk of falling (14–16) and increased risk of injury resulting from falls (17). The speed of voluntary stepping among older persons has been shown to be a strong predictor...
of falling, especially during dual-task (DT) condition, and is affected by slow central processing and executive functions that deteriorate with age. Other studies showed reduced step length (18,19), increased frequency of collisions between the swing and stance leg during lateral perturbations (19), more steps to recover balance during perturbation tests, and a second lateral step that follows forward or backward stepping (19,20) as indicators of an increased risk of falling. It appears that the lateral steps often emerge as a consequence of frontal plane instability arising after initiation of the first compensatory step (20). Thus, impaired ability to control the tendency of the CoM to fall laterally toward the unsupported side during step execution appears to be a particular problem for older adults.

In this study, we conducted a new analysis focusing on the variability of the magnitude of the side-to-side (ML) fluctuations and their changes over time during and immediately following rapid voluntary stepping. Previous research suggests that speed of voluntary stepping provides a discriminative measure of risk for falls. The variability of the ML fluctuations during and immediately after stepping was not measured. We propose to explore these fluctuations, which might reflect the underlying mechanism of the neural control of rapid stepping with demonstrated sensitivity to pathological alterations in the locomotor control system. This may help to document age-related changes in frontal plane stability and as a result fall risk and to objectively quantify improvements in response to therapeutic interventions. Thus, we aimed to examine whether frontal plane instability during and immediately following rapid voluntary stepping is different in groups of younger and older individuals. In addition, we asked whether the frontal plane instability is reduced during DT performance. We hypothesized that (a) older adults will demonstrate frontal plane instability during and immediately following rapid voluntary forward stepping and during DT condition compared with a younger population and (b) both study groups will demonstrate frontal plane instability compared with the single-task (ST) condition because cognitive theories claim that the available processing resources are limited. As a result, resource competition may occur during performance of more than one attention-demanding task, leading to difficulty with the motor task, especially in older adults (21).

**METHODS**

**Participants**

Seventeen older adults (aged 65–90), who live independently in the community, and 16 younger adults (aged 20–39) were recruited from senior community centers and a university population (Table 1). Older persons had to be at least 65 years of age, ambulate independently, score better than 24 on the 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 the study. Participants provided informed consent, in accordance with approved procedures by the Helsinki Ethics Committee in Soroka Medical Center, Beer-Sheva, Israel.

**Sample Size Estimation**

Separate calculations were performed to determine sample size requirements based on voluntary step execution (ie, foot contact time) in ST and DT conditions. For both calculations, the probability of Type I error was .05 and the probability of Type II error was .2. In Melzer and Oddsson (14), the step execution times (forward stepping) of older adults were 300 and 450 ms longer in ST and DT conditions, respectively, in comparison with those of younger adults. Using net reduction values in combination with standard deviations of 250 and 300 ms, it was determined that at least 12 and 10 participants per group would be required, respectively.

**Experimental Protocol**

A total of six voluntary forward step execution trials were conducted for each participant, under ST and DT conditions (three trials in each condition). The participants were instructed to stand comfortably and barefoot on a force platform, dividing their weight evenly between both legs. A space of 6 cm between the heels and a normal 10° external rotation was the starting position. Foot placement was marked on the force plate in order to ensure each step started from the same position. The participants were instructed to step as quickly as possible following a tap cue on the heel provided manually by the experimenter (shear ground reaction forces greater than 15 N).

| Table 1. Participant Characteristics for Both Groups |
|---------------------------------------------------|
| Characteristic, Mean ± SD                      | Old (n = 17) | Young (n = 16) |
| Age (y)                                         | 77.6±6.6*   | 27.7±7.5       |
| Gender (% males)                                | 41         | 31             |
| Mini-mental test score                         | 28.4±2.4*  | 30             |
| Number of medications                          | 3.5±1.3*   | 0              |
| Weight (kg)                                     | 73.3±12.5* | 67.8±7.8       |
| Height (cm)                                     | 162.3±7.3  | 173±9.5        |
| Berg Balance test                               | 53±2.9*    | 56             |
| Voluntary stepping time, ST (ms)               | 888.9±191* | 718.8±95       |
| Voluntary stepping time, DT (ms)               | 1186.9±330° | 880.2±114°     |

Notes: DT= dual task; ST= single task.

*p value compares baseline mean ± 1 SD in the two groups and, unless otherwise indicated, are based on Mann–Whitney U tests.

*Statistically significant differences between older and younger adults (p ≤ .05).

†Statistically significant differences between DT and ST conditions within age groups (p ≤ .05).
and less than 25 N) on the heel, outside the force plate into a target marked in front of the participant, and were instructed to remain standing for 5 s immediately following rapid stepping. Following the step, participants were allowed to respond in a “natural” manner (no instructional constraints). Steps included in the analysis were 50–60 cm long and were always performed with the dominant leg as chosen by the participant; steps that were longer or shorter were extracted from the analysis. In the ST condition, participants were asked to focus their gaze on an “X” displayed on a large screen placed 3 m in front of them. During the DT condition, participants looked at the same screen and performed a modified Stroop test while waiting for the cutaneous cue as described in detail elsewhere (14). The participants were instructed to name the colors of the inks, as quickly as possible, until the end of the procedure. No prioritization was given and the participants were asked to perform both tasks as best as they could. The modified Stroop test was used because the test requires considerable focused attention and few instructions to perform. In addition, it requires only direct verbal responses, does not address memory, and shows relatively small long-term learning effects.

Ground reaction force and CoP data during step execution tests were sampled at a frequency of 200 Hz and collected using suitable software (BioWare v.3.24, Kistler Instrument Corp). Force platform data were analyzed using custom-made code written in MatLab version 6 (MathWorks Inc, Natick, MA). The following events were extracted from the ground reaction force data (cf. Figure 1): (a) the tap cue was detected as a spike in the shear ground reaction forces (Fy) in the anterior–posterior direction (C in Figure 1); (b) the step initiation was detected as the first ML deviation of the center of pressure (COP) toward the swing leg (A in Figure 1); (c) foot off (FO in Figure 1) was defined as the sudden change in the slope of COP toward the stance foot in the ML direction; (d) foot contact (FC in Figure 1) was defined as the onset of unloading in the vertical ground reaction force; (e) preparatory duration was calculated as the time from step initiation to foot off; (f) the swing duration was calculated as the time from foot off to foot contact; and (g) the overall step was calculated as the time from the tap cue to foot contact (14,22). Intraclass correlation coefficients (ICC (1,2)) were good to excellent across all parameters and test conditions (0.62–0.88 [22]).

Additional code written in MatLab (version R2008b, MathWorks, Natick, MA) was used to measure side-to-side (ie, in the ML direction) CoP fluctuations over time (ie, the frontal plane variability) in three different time frames: (a) during the swing phase, that is, the duration between foot off and foot contact (Example in Figure 1); (b) during the initial contact phase, that is, the time between foot contact and 250 ms after the foot contact; and (c) during the loading phase, that is, the time between 250 and 500 ms following foot contact completing the step. The following parameters were obtained: the average ML sway CoP fluctuations and the average distance (in mm) the CoP travels from side to side (Figure 1). CoP fluctuation was defined as each point at which the CoP traveled to the right side, then changed its direction in the frontal plane and traveled to the left. This event was automatically detected by searching for the first sample where the ML–CoP peaked to the right side of the curve to the next sample in which CoP peaked to the left side of the curve (Figure 1).

Figure 1. Example of mediolateral center of pressure (ML-CoP) fluctuations of an older adult during and following the swing phase of the voluntary step test. Figure on the right shows CoP right-to-left fluctuations in the frontal plane (see Methods section for explanations).
Statistical Analysis

Shapiro–Wilk test was used to test the normality of the preselected set of variables pooled over the sample population and for both groups independently. Because the variables were not distributed normally, participant characteristics (eg, age, Mini-Mental State Examination, weight, height, Berg Balance scores, and voluntary stepping times) were compared using Mann–Whitney U tests. To examine the first purpose of the study, we employed Mann–Whitney U tests to compare between groups (younger vs. older adults) and Wilcoxon signed-ranks test to compare between task conditions (ST vs DT). The dependent variables included (a) the average distance of all ML sway CoP fluctuations (in mm); (b) standard deviation of ML-CoP range; and (c) the coefficient of variation (CV) of ML-CoP range (CV = SD/mean × 100) during the swing phase, the initial contact phase, and the loading phase. A full Bonferroni correction (α level = 0.05/3) was used for each of the three nonparametric tests during each of the three phases to achieve an overall significance level of 0.017.

In addition, in order to test whether the speed of forward stepping is limited by the ability to control balance during the step, the associations between the variability measures with the speed of stepping was evaluated using partial Spearman correlations controlled for age (p). All statistics were analyzed using SPSS (version 16, Chicago, IL).

RESULTS

As seen in Table 1, there were statistically significant differences across almost all parameters other than gender. For example, in ST condition, the voluntary stepping time in older adults was 24% slower than in younger ones, and 35% in DT condition. Also, the step times in DT condition were always slower than in ST condition for both study groups.

There were statistically significant age-related differences only in the CV of ML-CoP ranges that represent the variability of the side-to-side (ML) fluctuations over time during and immediately following the rapid voluntary stepping. Table 2 shows that during the ST condition, the CV of ML-CoP range was 25% higher for older adults at the loading phase (p = .001) compared with their younger counterparts and approached significance at the swing phase (p = .03) and at the initial contact phase following stepping (p = .07), 15% and 11% higher for older adults, respectively. Under the DT condition, the differences in CV of ML-CoP range were 29.5%, 17.8%, and 9% higher for the older adults during the swing phase (p = .001), the initial contact phase following stepping (p = .001), and the loading phase (NS), respectively (Table 2).

For DT compared with ST, within-group analysis revealed no significant differences in any of the parameters representing the side-to-side (ML) fluctuations over time during and immediately following the rapid voluntary stepping (Table 2).

In general, there were no correlations between the speed of forward stepping and the variability measures apart from high positive correlations between CV of ML sway during swing phase and speed of stepping in both ST and DT conditions (ρ = 0.86, p = .001 and ρ = 0.70, p = .002, respectively). A positive correlation indicates that faster stepping was associated with less variability, that is, better control of ML-COP fluctuations during rapid stepping. In addition, mean ML sway during swing phase in ST condition and mean ML sway during initial contact phase of DT condition showed negative correlations with the speed of stepping in milliseconds (ρ = −0.67, p = .006 and ρ = 0.56, p = .025, respectively). Negative correlations indicate that the faster the speed of stepping the higher the mean ML sway ranges.

DISCUSSION

In this study, we sought to quantitatively compare age-related changes in ML control during and following rapid voluntary stepping and the effects of a concurrent attention-demanding cognitive task. The results partially support our first hypothesis; although there were no significant age-related differences in mean and standard deviations of ML-CoP ranges, we found that the CV of ML-CoP

| Task Condition | Old        | Young      | ρ Value |
|----------------|------------|------------|---------|
| A. Single task|            |            |         |
| Swing phase (mm) | Mean       | 2.1±0.2    | 0.88    |
| SD             | 2.2±0.2    | 2.3±0.4    | 0.78    |
| CV             | 11.2±5.2   | 97.8±4.1   | 0.03    |
| Initial contact phase | Mean       | 2.5±0.3    | 0.17    |
| SD             | 2.65±0.4   | 2.7±0.3    | 0.8     |
| CV             | 100±4.7    | 89.7±3.1   | 0.07    |
| Loading phase  | Mean       | 4.6±0.4    | 0.05    |
| SD             | 4.3±0.4    | 5.4±1      | 0.37    |
| CV             | 92.6±4.5   | 74.1±3.2   | 0.001   |
| B. Dual task   |            |            |         |
| Swing phase (mm) | Mean       | 2.3±0.3    | 0.64    |
| SD             | 3.1±0.4    | 2.0±0.2    | 0.02    |
| CV             | 129.4±5.8  | 99.9±4.6   | 0.001   |
| Initial contact phase | Mean       | 4.8±1      | 0.18    |
| SD             | 4.4±0.5    | 3.8±0.5    | 0.36    |
| CV             | 116.5±4.2  | 99.1±3.9   | 0.003   |
| Loading phase  | Mean       | 4.2±0.8    | 0.12    |
| SD             | 3.5±0.6    | 2.8±0.2    | 0.05    |
| CV             | 89.6±4.3   | 82.1±3.8   | 0.18    |

Notes: CV = coefficient of variation; ST = single task; DT = dual task. Values shown represent mean, SD, and CV of step execution parameters for younger and older persons for ST (three trials) and DT (three trials) ± symbol 177 “Symbol” × 121 SD. A full Bonferroni correction (α level = 0.05/3 = 0.017) was used for each of the three nonparametric tests during each of the three phases to achieve an overall significance level of .05. There were no significant differences between ST and DT.
ranges that represents the variability of frontal plane fluctuations was significantly higher in older adults compared with younger controls under both task conditions. We also found that participants with faster voluntary stepping times showed lower frontal plane fluctuations as presented by the CV of ML-CoP ranges. On the other hand, our second hypothesis was rejected; cognitive task had no influence on any measure of frontal plane fluctuations in both age groups.

To our knowledge, this is the first study that explores frontal plane fluctuations and their changes over time during and immediately following rapid voluntary stepping among an older population in comparison to that of a younger population. During and immediately after rapid stepping, the body is highly unstable in the frontal plane, since only one foot is loaded during the swing phase, and since after the completion of stepping, feet are placed in a narrow base of support (ie, one foot in front of the other). The frontal plane fluctuations may convey important information that may be useful in understanding the age-related alterations in balance control and in functional status. Our analysis reveals that participants with faster stepping times were able to better control ML movement during step (ie, lower CV of ML-CoP ranges). In view of the results from previous research, this is not surprising. Investigating the association of speed of stepping and CV, measures may suggest that the speed of forward stepping is limited (either consciously or subconsciously) by the ability to control CoP movement during the step. Thus, anticipation of inability of controlling ML movement during and following rapid stepping will cause slower stepping times. This finding supports the notion that ML variability may play an active role in balance control during and following rapid stepping. It is of particular interest that the older and slower group demonstrated greater ML variability compared with the younger and faster group.

In this study, we analyze instability using an approach similar to that used by Hausdorff and colleagues (23) measuring gait variability and Lippsitz and colleagues (24) measuring heart rate variability (Figure 1). At least in the older population, frontal plane instability (ie, variability) during and immediately after stepping reflects more than just musculoskeletal mechanics. The association between step execution and ML fluctuation variables (Table 3) suggests that the CV of ML-CoP ranges was the only variable that was positively correlated with slower stepping speed, which was found previously to be related to a better balance control (14), falls (16), and even injury from fall (17) in older adults. More generally, this initial work suggests that just as there is much to be gained by investigating gait and heart rate dynamics, above and beyond the study of the average heart rate and gait dynamics, similar investigations of step dynamics may provide insight into balance control and may also have clinical applications.

Evaluation of the underlying mechanisms that may be involved in these age-related changes include (a) increased active muscle stiffness due to coactivation, (b) decreased lower limb muscle force, and (c) increased sensory detection thresholds. Collins and De Luca (25) and Laughton and colleagues (26) suggested that age-related increases in postural sway during standing were due, in part, to an increase in muscle activity in the lower limbs. The force output of skeletal muscle contains noise-like fluctuations (27) that increase with increased muscle activity (28), thus, suggesting increased postural sway. Although electromyographic activity was not measured in this study, our results may be interpreted as an increase in hip abductor muscle activity on both sides in older persons to gain balance on the frontal plane. Greater coactivation may be due, in part, to compensation for a decrease in lower limb muscle strength and power (26). Laughton and colleagues (26) suggested that increasing muscle coactivation is an attempt to increase stability under conditions of muscle weakness with increasing age. Thus, weakness in hip joint abductor muscles could potentially impair an individual’s ability to effectively control balance in the ML direction. Thus, possibly by using muscle coactivation strategy, older participants demonstrated a Bernsteinian freezing of degrees of freedom (29) in the ML direction resulting in rigidity that could lead to an increase in ML fluctuations in the frontal plane. Another explanation for increased muscle coactivation given by Laughton and colleagues (26) suggest that an increased level of muscle activity may enhance joint proprioception by increasing the firing rate and recruitment of primary afferents, thus increasing sensory detection thresholds. This is relevant because reactive muscle coactivation might be a strategy of increasing proprioceptive input.

Unexpectedly, frontal plane instability was not affected by a concurrent cognitive task; there were no differences between ST and DT conditions. Zilstra and colleagues (30), in their systematic review, and Swanenburg and colleagues (13) revealed no added value of cognitive tasks for fall prediction, but unlike our testing procedure, these were quantitative studies of quiet standing (ie, quasi-static condition) while we measure ML dynamics in a more dynamic situation (ie, rapid voluntary stepping). In addition, unlike the studies above (13,30), our sample consisted of younger versus elderly persons whose stepping ability was previously found to be affected by DT (14,16,17). One could argue that older participants in this study were already operating close to their ML stability boundaries under ST conditions, and therefore could not “afford” to sway even more, and (unconsciously) focused on keeping their balance during the DT. Thus, the explanation would be that during the swing phase and immediately after completion of the step, participants from both study groups focused their attention exclusively on balancing, ignoring the cognitive task (ie, posture first strategy); thus, the cognitive task was actually not harmful for task performance. This explanation is supported by the following observations: Under DT conditions, participants occasionally did not...
perform the concurrent cognitive task, that is, stop talking while performing the stepping task; furthermore, older participants had a tendency to look down prior to and during the stepping although they were instructed to maintain a forward gaze. Our recent studies suggest that concurrent attention-demanding tasks usually interfere with the initial phases of stepping, whereas the terminal phases where the actual movement is already executed are less affected (16,17). This study has several limitations. First, cognitive performance in ST condition was not measured in this study, and therefore, cognitive task cost could not be calculated. The second limitation is that the data came from a fairly small sample of relatively healthy independent, medium–high socioeconomic class, with underrepresentation of unhealthy and poor older adults. The third limitation is that differences in stepping speeds between older and younger adults may also reflect differences in the variability of ML movement during and following rapid stepping. Moe-Nilssen and Helbostad (31) suggested that when differences in the variability measures are reported between populations demonstrating different walking speeds, results may be biased. This may be the case for differences in variability measures, as introduced by the strong association between CV measures and speed of stepping; however, results should be treated with caution due to our small and relatively healthy sample of older adults. Investigating the speed dependency at different stepping speeds will be the next step in research in this field. This should involve larger sample sizes and explore differences between populations of older adults with different balance control abilities, such as between fallers and nonfallers.

In conclusion, this study suggests that frontal plane fluctuations are more variable in older adults compared with those in younger adults and that cognitive task did not influence the variability of CoP fluctuations.

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