A kinematic analysis of the rapid step test in balance-impaired and unimpaired older women

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Abstract

Little is known about the kinematic and kinetic determinants that might explain age and balance-impairment alterations in the results of volitional stepping performance tests. Maximal unipedal stance time (UST) was used to distinguish “balance-impaired” old (BI, UST < 10 s, N = 15, mean age = 76 years) from unimpaired old (O, UST > 30 s, N = 12, mean age = 71 years) before they and healthy young females (Y, UST > 30 s, N = 13, mean age = 23 years) performed the rapid step test (RST). The RST evaluates the time required to take volitional front, side, and back steps of at least 80% maximum step length in response to verbal commands. Kinematic and kinetic data were recorded during the RST. The results indicate that the initiation phase of the step was the major source of age- and balance impairment-related delays. The delays in BI were primarily caused by increased postural adjustments prior to step initiation, as measured by center-of-pressure (COP) path length (p < 0.003). The Step landing phase showed similar, but non-significant, temporal trends. Step length and peak center-of-mass (COM) deceleration during the Step-Out landing decreased in O by 18% (p = 0.0002) and 24% (p = 0.001), respectively, and a further 12% (p = 0.04) and 18% (p = 0.08) in BI. We conclude that the delay in BI step initiation was due to the increase in their postural adjustments prior to step initiation.

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1. Introduction

Falls are a leading cause of accidental death and injury for those over the age of 65 years [1] and older women, especially those with balance impairments, are at a particularly high risk for fall-related injuries [2]. Recovery from an imminent fall has been shown to be dependent on the ability to take a rapid and adequately long step in the direction of the fall [3–5]. Tests of volitional stepping, which are distinct from involuntary compensatory stepping used to prevent falls, might be used in a clinical setting to predict falls. Compared to laboratory-based postural perturbations, volitional stepping tests are simpler to conduct, and by experimentally varying the certainty of stepping direction, the presence or absence of a cognitive load, and the amount of weight shift required, they can provide an equivalent postural challenge.

Indeed, complex stepping reaction time (from visual trigger to foot-ground contact) has been found to be an independent predictor of falls [6]. Moreover, the ability to take a maximal step and return to the initial position (the Maximum Step Length or MSL test) is as good a predictor of mobility performance, frequent falls, self-reported disability, and fear of falling as standard measures such as unipedal stance time [7]. Based on the MSL, the Rapid Step Test (RST) [8] tests the ability to execute near-maximal, rapid, consecutive, volitional steps in response to verbal

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commands. The RST records the time to take 24 steps, of length 80% of the MSL, to the front, side, and back using either foot. Healthy young subjects take less time than unimpaired old, and unimpaired old subjects take less time than balance-impaired old subjects [8]. The RST time was also highly correlated ($r = 0.6–0.9$) with various balance and strength measures [8]. While these findings are useful for clinical evaluation, the specific age-related and balance impairment-related kinematic changes in performance that account for the RST time differences remain unclear.

While the age- and impairment-associated increases in RST time might have been due to differences in reaction time [6,9], it has been observed clinically that the transition from one consecutive step to the next appears to be more difficult for the older and more impaired subjects. Furthermore, rapid weight shifting from foot to foot just prior to step initiation has often been observed during prior RST testing [7,8] of older and more impaired subjects. The older and more impaired subjects in these studies also seemed to have particular difficulty in returning themselves to the upright starting position from the feet-apart position. The purpose of this study was to use kinematic and kinetic analyses to explore the underlying causes for those clinical observations.

We hypothesized that the age- and balance impairment-associated delays in the RST would be manifest only during: (1) initiation of the Step Out and (2) the ability to return to the starting position. Based on clinical observation of the initiation of the Step Out, we expected to observe greater weight shifting during the preparation to step. This would be indicated by greater motion of the center-of-pressure (COP) under both feet just prior to step initiation. Similarly, we expected the older and more impaired subjects to exhibit a reduced ability to return to the starting position. We also predicted this reduced ability to be due to difficulty in reversing their outward center-of-mass (COM) velocity (momentum) with the stepping leg after the landing of the Step Out and prior to the return step lift off. The results of testing these hypotheses should provide insight into age- and balance-impairment associated alterations in stepping control and, by inference, kinematic performance parameters responsible for the age- and balance-impairment increase in fall risk.

### 2. Methods

#### 2.1. Subjects

Thirteen healthy young females (Y), 12 unimpaired older females (O), and 14 balance-impaired older females (BI) participated in this study (Table 1). Three trials measuring maximum unipedal stance time (UST) with the eyes open were used to define balance-impairment [10]: All Y and O were capable of UST > 30 s, while all BI had UST < 10 s. All Y completed a medical questionnaire and all O and BI were physically screened by a physician–geriatrician prior to testing. While the O had minimal findings on directed history and physical examination, one-third of the BI noted pain or limitations in motion of the hip or knee, nearly half noted problems with their balance, and, on exam, four (26%) had mild hip flexion weakness and two (13%) had a positive Romberg sign. There were no significant differences in weight, height, or BMI between Y and O, or between O and BI; although the BI had a tendency to be older than the O, this difference was not significant ($p$: N.S.).

#### 2.2. Protocol

The maximum step lengths (MSL) of each subject to the front, back, and side were first determined for each foot by taking the average of five trials in each direction (Fig. 1). Subjects wore their own running or athletic shoes and were required to begin each trial from a comfortable position within the starting box with their arms crossed. The starting box was a 35.6 cm wide × 30.5 cm long tape rectangle on the floor. As in previous work [7,8], the MSL was defined as the ability to take a maximal length Step Out and then return to the starting box, using a single step. The base (support) leg had to remain in contact with the floor and to not lift off during the step, although the heel was allowed to lift off for front steps. Colored tape was used to mark a line at 80% of the subject’s MSL on the floor, to the nearest 2.54 cm. These marks were the targets for the RST.

Commands for the RST were given verbally by a single experimenter: e.g. “right front”, “left side”, etc. After the initial command, all successive commands were given as the subject returned from the previous step. All steps were performed successively and the instructions to the subject

### Table 1

Mean (S.D.) subject demographics

<table>
<thead>
<tr>
<th></th>
<th>Young (Y)</th>
<th>Older (O)</th>
<th>Older Balance-Impaired (BI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>13</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Mean age (years)</td>
<td>23 (4)</td>
<td>71 (6)</td>
<td>76 (7)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.67 (0.08)</td>
<td>1.61 (0.08)</td>
<td>1.6 (0.06)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>61 (6)</td>
<td>62 (10)</td>
<td>67 (11)</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>22.1 (3.2)</td>
<td>b</td>
<td>26.1 (3.3)</td>
</tr>
<tr>
<td>Unipedal stance time* (s)</td>
<td>b</td>
<td>b</td>
<td>5.5 (3.2)</td>
</tr>
</tbody>
</table>

* Value shown is best effort of three attempts.

b All subjects exceeded 30 s.
were to complete the test “as quickly and accurately as possible while keeping your arms crossed”. Each subject performed the same randomized stepping sequences. After a brief practice session to familiarize the subjects with the step target locations and test rules, three practice trials were conducted: 6 steps with the right leg only, 6 steps with the left leg only, then 12 steps with either leg. Finally, one sequence of 24 steps was then performed and analyzed. An error was recorded if the subject: (i) did not reach the target line, (ii) did not return to the starting box with a single step, (iii) uncrossed her arms, (iv) stepped with the wrong foot, or (v) stepped in the wrong direction. All errors were visually determined by a single experimenter.

2.3. Data collection

Each foot was initially located on a ground-level force plate (OR6-7-1000, AMTI, Watertown, MA). Metallic switch plates were located at the Step Landing positions such that foot-ground contact time was signaled to the computer by completion of a circuit between metal tape under the shoe and the switch plate. Optoelectronic markers (Optotak 3020, Northern Digital, Inc., Waterloo, Canada) were placed on the left and right fifth metatarsophalangeal joints, lateral malleoli, lateral femoral condyles, greater trochanters, and acromion processes to acquire kinematic data. All data were sampled at 100 Hz.

2.4. Data processing

Custom software routines in Matlab (v6.5, Natick, MA) were used to process all data and thresholds, determined from pilot data, were reliably used to detect stepping. Step liftoffs were indicated by the vertical ground reaction force dropping below 3% body weight or, as a backup, a 0.4 m/s foot marker velocity threshold. Step landings were determined by foot switchplate contact or, as a backup, the same foot marker velocity threshold and all identifiable steps greater than 25 cm were included in the analysis. In the trials that were checked manually (at least one-third of each group) no steps were incorrectly identified and the liftoff and landing times determined by the force plate, switch plate, and foot marker velocity thresholds closely agreed with visual observation and with one another. The step durations as well as the whole-body COM and step foot displacements, velocities, and accelerations in the step direction were calculated. Note that while the target step length was set to 80% of MSL, the actual step displacement varied and was therefore included as additional variables. RST time was determined by a single experimenter using a stopwatch that was started with the first verbal command and stopped when the last step contacted the ground in the starting box.

The ankle joint centers were located at half of intermalleolar width from the lateral malleolus in the medial direction. The knee joint centers were similarly located at half of the knee width from the lateral femoral condyles in the medial direction. The hip joint centers were located at the points medial to the greater trochanters that resulted in the minimal fluctuation in their respective thigh segment length during the RST for each subject. The segment masses of the feet, shanks, thighs, and HAT were determined from the literature in terms of percentage of body mass [11]. Likewise, the COM locations of the feet, shanks, and thighs were determined as a percentage of the calculated segment length along the long axis of the segment [11]. The position of the HAT COM in the anterior and superior direction was calibrated for each subject from the COP position and the position and mass of the other body segments during quiet stance. Joint rotations and angular velocities and whole-body COM position, velocity, and acceleration were calculated using custom algorithms implemented in Matlab using methods based on Vaughan et al. [12]. Further methodological details and the Matlab files used are available from the corresponding author upon request.

Variations in COP position frequently precede volitional steps from static stance and prepare the body to make an effective step. These variations follow a distinct pattern and have been called anticipatory postural adjustments (“APAs”). An APA requires that the step begin from quiet stance. As such, APAs cannot be identified for the RST because it consists of a series of steps with no consistent static reference points upon which to base the measurement of APAs. Thus, the COP path length was used as a measure of postural control during the feet-together, double support portions of the RST. COP path length was defined as the total cumulative distance traveled by the COP under both feet from the landing of the prior return step to the liftoff of the current step. The COP path length was calculated by summing the point-to-point distances traveled by the COP during every data frame during this period. While the
occurrence or non-occurrence of an APA is a discrete measure of anticipatory activity that relies on a specific threshold level and requires that the step begin from quiet stance. COP path length is a continuous measure that does not rely on a threshold and takes into account all directions of COP motion during prior return step landing and the preparation for the subsequent step lift off. COP path length has been used to evaluate both gait [13] and static balance [14] and appears to be more appropriate for analyzing a multi-directional, multi-phase stepping task such as RST.

A single value for each variable tested was determined for every subject in each step direction (front, back, and side) by calculating the mean values for all acceptable steps in that direction. The steps were also subdivided by phase: ‘Step Preparation’ was defined as the period from the preceding step landing to the current step liftoff, ‘Step Out’ was the single support period when the stepping foot is airborne and traveling to the “out” landing position, ‘Step In’ was the single support period while the stepping foot is airborne and returning to the starting position, and ‘Step Landing’ was the period of double support between Step Out and Step In (Fig. 2). Fig. 3 shows a sample COP path, as well as COM and anterior displacement data for representative Y, O and BI subjects. Mean values for all complete front, back, and side steps for COP path length; peak stepping foot displacement, velocity, and acceleration; peak COM displacement and velocity were determined for each subject for all appropriate step phase time intervals. Additionally, the change (maximum–minimum) in COM velocity and peak COM deceleration during the “Step Landing” phase were determined.

2.5. Statistical analysis

Independent sample t-tests were used to test for age- and balance-impairment differences on the clinical measures—MSL, RST time, and RST errors. Repeated measures analysis of variance was used to test all kinematic and COP parameters using the step direction (front, back, or side) as the repeated measure and subject group as an independent variable. Because we were only concerned about the separate effects of age and balance-impairment, separate analyses were performed for Y versus O (age effect) and O versus BI (balance-impairment effect). P < 0.05 was considered statistically significant.

3. Results

3.1. Clinical measures

Mean MSL was significantly longer in the Y than O (age effect, p < 0.0001), and in the O than the BI (balance-impairment effect, p < 0.05, Table 2). RST time tended to be longer in the O than the Y and was significantly longer in the BI than the O (p < 0.05), but no age or balance-impairment-related differences were found in the number of errors.
committed. As greater MSL distances and lesser RST times both indicate improved performance, these measures were combined by dividing mean MSL distance by RST time. The resultant parameter also differentiated Y from O (\(p < 0.0001\)) and O from BI (\(p < 0.05\)).

### 3.2. Time breakdown of RST by step phase

The Y required significantly less time than the O (\(F = 6.5, p < 0.02\)) and the O needed less time than the BI (\(F = 16.2, p < 0.0005\)) for the Step Preparation phase (Fig. 4), thereby supporting our first hypothesis. The duration of the Step Landing phase showed similar trends, but because they were non-significant our second hypothesis was not supported. The Step Out and Step In durations were similar in all three groups, but the trend in durations was the inverse of the dual-support phases: the Y took the most time and the BI took the least time.

#### 3.3. Step Preparation phase

The BI used greater COP path lengths (see Fig. 3 for sample data) than the O (O = 16.8 ± 6.4 cm, BI = 23.2 ± 8.4 cm, \(F = 11.6, p < 0.003\)) but there was no COP path length increase in O versus Y (Y = 15.7 ± 6.3 cm, \(F = 0.43, p: \text{N.S.}\)).

#### 3.4. Leg swing (Step Out and Step In) phases

The Y had significantly larger foot and COM displacements and velocities, and foot accelerations, during both the Step Out and Step In phases than did the O (Table 3).

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>Young (Y)</th>
<th>Older (O)</th>
<th>Older Balance-Impaired (BI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSL (m)</td>
<td>0.97 (0.07)(^a)</td>
<td>0.81 (0.01)</td>
<td>0.72 (0.10)(^a)</td>
</tr>
<tr>
<td>RST time (s)</td>
<td>41.4 (4.8)</td>
<td>44.4 (4.6)</td>
<td>55.6 (16.9)(^a)</td>
</tr>
<tr>
<td>RST errors</td>
<td>3.23 (2.35)</td>
<td>3.42 (2.23)</td>
<td>4.87 (3.52)</td>
</tr>
<tr>
<td>MSL/RST (m/s)</td>
<td>0.024 (0.002)(^b)</td>
<td>0.018 (0.003)</td>
<td>0.014 (0.003)(^a)</td>
</tr>
</tbody>
</table>

\(^a\) Age effect noted in the Y column and Balance-Impairment effect noted in the BI column \(p < 0.05\).

\(^b\) Age effect \(p < 0.0001\).

### Table 3

<table>
<thead>
<tr>
<th>Step Direction</th>
<th>Variable</th>
<th>Young (Y)</th>
<th>Older (O)</th>
<th>Older Balance-Impaired (BI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Out</td>
<td>Foot displacement (cm)</td>
<td>80 (9.5)(^c)</td>
<td>66 (12)</td>
<td>58 (12)(^a)</td>
</tr>
<tr>
<td></td>
<td>Foot peak velocity (m/s)</td>
<td>2.79 (0.46)(^b)</td>
<td>2.30 (0.43)</td>
<td>2.06 (0.41)(^a)</td>
</tr>
<tr>
<td></td>
<td>Foot peak acceleration (m/s²)</td>
<td>21.1 (5.8)(^c)</td>
<td>17.1 (4.7)</td>
<td>15.2 (4.2)</td>
</tr>
<tr>
<td></td>
<td>COM displacement (cm)</td>
<td>26 (6.2)(^c)</td>
<td>19 (6.6)</td>
<td>16 (5.8)</td>
</tr>
<tr>
<td></td>
<td>COM peak velocity (m/s)</td>
<td>0.78 (0.16)(^c)</td>
<td>0.61 (0.18)</td>
<td>0.53 (0.16)</td>
</tr>
<tr>
<td>Step In</td>
<td>Foot displacement (cm)</td>
<td>81 (9.8)(^d)</td>
<td>66 (11)</td>
<td>57 (13)(^c)</td>
</tr>
<tr>
<td></td>
<td>Foot peak velocity (m/s)</td>
<td>2.80 (0.37)(^c)</td>
<td>2.36 (0.42)</td>
<td>2.12 (0.46)</td>
</tr>
<tr>
<td></td>
<td>Foot peak acceleration (m/s²)</td>
<td>16.7 (4.8)(^c)</td>
<td>13.4 (3.3)</td>
<td>12.9 (3.3)</td>
</tr>
<tr>
<td></td>
<td>COM displacement (cm)</td>
<td>24 (5.7)(^c)</td>
<td>17 (5.9)</td>
<td>14 (5.0)</td>
</tr>
<tr>
<td></td>
<td>COM peak velocity (m/s)</td>
<td>0.79 (0.19)(^c)</td>
<td>0.59 (0.20)</td>
<td>0.52 (0.16)</td>
</tr>
</tbody>
</table>

\(^a\) Age effect noted in the Y column and Balance-Impairment effect noted in the BI column \(p < 0.05\).

\(^b\) Age effect \(p < 0.0005\).

\(^c\) Age effect \(p < 0.005\).

\(^d\) Age effect \(p < 0.0001\).
Similar trends were evident between O and BI, with significance reached for step foot displacement during Step In and Step Out and for step foot velocity during Step Out only.

3.5. Step Landing phase

The Y had a significantly larger change in COM velocity and greater COM deceleration than the O did during Step Landing (Table 4). A similar, non-significant, trend existed between the O and BI. Greater step distances were significantly correlated with both COM velocity change (Pearson \( r = 0.69, p < 0.0001 \)) and peak COM deceleration (Pearson \( r = 0.65, p < 0.0001 \)).

3.6. Step direction

Every variable that had a significant group effect also had a significant effect of step direction (Table 5). Front steps had the greatest COM excursions and velocities during the Step Out and Step In and the greatest change in COM velocity during Step Landing. Side steps required the least time and shortest COP path length in the Step Preparation phase and had the least stepping foot displacement, velocity, and acceleration during the Step Out and Step In. Back steps had the lowest peak COM decelerations during the Step Landing phase. No consistent interaction effects of group and step direction were observed.

4. Discussion

We found that increases in RST time in older adults, particularly significant in the BI, were due primarily to a prolongation of the Step Preparation phase, thus supporting our first hypothesis. While similar trends were evident during the Step Landing phase (Fig. 4), neither of the age nor the balance-impairment effects reached significance and our second hypothesis was not supported. During the Step Preparation phase we found an increase in postural adjustments, as measured by COP path length. During the Step In and Step Out phases, larger displacement, velocity, and acceleration of the COM and stepping foot allowed the Y (compared to the O) and the O (compared to the BI) to traverse a greater distance in a similar time period. During the Step Landing phase the change in COM velocity and difference in peak accelerations during the Step Landing indicated that the attenuation of the step momentum and the subsequent pushback to the start position during the Step Landing was more difficult for the O relative to the Y, and particularly so for the BI relative to the Y.

4.1. Step Preparation

Previous studies have found that both reaction time and step liftoff time increase with age for similar stepping tasks [9,15] and that older subjects have a proportionately larger increase in weight transfer time compared to reaction time.
[15], where step liftoff time is the sum of the reaction and weight transfer times. Some of the observed delay in Step Preparation was almost certainly due to a delay in reacting to the verbal command (a complex reaction time task). Based on the findings of others [9,15], we believe these slower reaction times to be the most likely cause of the age-related increase in Step Preparation delay, although we had no practical way of measuring reaction time for the task tested here. However, the present data indicate that impaired postural preparation, i.e., group differences in COP path length, played a large role in the BI delays in Step Preparation. Although postural preparation delays appear to be responsible for a portion of the Step Preparation delay between the O and BI, further research is necessary to determine the proportion of this delay that can be attributed to postural factors, such as those noted above, versus cognitive processing delays (i.e., simple or choice reaction time) which were not measured in this study. The Step Preparation delay may represent an adaptation to age- and impairment-related changes in postural control. These adaptations have interesting implications for the ability of the RST to quantify the capacity to multitask or divide attention among multiple simultaneous subtasks (for example, execute current step while listening to step direction command and planning the subsequent step). We feel that these aspects of the RST merit further study in combination with other neuropsychological measures of these capacities.

4.2. Leg swing

The Y stepped significantly farther than the O over essentially the same time interval. They accomplished this by moving their stepping foot, and COM, with greater velocities and accelerations. This raises the question of whether faster steps permit longer steps to be taken or whether longer steps require the foot to move faster. We could not definitively answer this question with the data collected, but different stepping tasks may involve different requirements in this regard.

4.3. Step Landing

While the stepping foot was at near-maximal step distance, the Y both landed and lifted off with greater COM velocities than the O. The reasons for this are unclear because older subjects could have been either less willing (distance limits COM motion) or less able (COM motion limits distance) to step as far as the Y. If the former is true, then this volitional stepping task may be a poor predictor of the capacity of the elderly to take a rapid step to prevent a fall, as has previously been reported [16] for a test based primarily on the temporal properties of the step initiation. However, if our hypothesis is supported and step distance is limited by the ability to control COM motion, as suggested by the correlation of the MSL and RST with fall risk [7,8], then knee or hip torque, power or rate of torque or power development may play a significant role in the ability to execute a large step. While step initiation has been the focus of substantial attention in the literature, the landing of both volitional and compensatory steps has received comparatively little consideration.

Compensatory stepping to prevent falling requires the subject to swing the foot rapidly into position, and then arrest the remaining body momentum. This second point is often neglected in the literature, as moving platforms, widely used to cause balance perturbations, accelerate the feet prior to the body and their deceleration phase can act to restabilize the subject [17–19].

One might speculate that an inability to rapidly apply a sufficient force to the ground with the stepping leg in order to return to the starting position in a single step, as required by the RST, is a potential predictor of inadequate leg strength. Indeed, these same subjects were also tested in a compensatory stepping task in response to waist pulls [20] and the BI were found to be less able than the O to attenuate the momentum imparted by the pull.

4.4. Limitations

Despite our effort to age-match the two older groups, the BI were slightly older than the O. However, additional repeated measures analyses of variance using age as a continuous factor indicated that this age difference had little effect on the results.

The auditory cue to step (i.e., verbal command) was used in order to free the eyes to fixate on the step location. The verbal command was issued based on the expectation that the subject would return to his/her starting position. Subjects who did not step properly because they made an error (defined in Methods) extended their RST time. On the other hand, subjects who exhibited no errors facilitated the issuance of rhythmic verbal commands; this entrainment might have prevented certain subjects from using their maximum stepping speed.

The lack of ground reaction force data during Step Landing was regrettable. The four additional force plates that would have been required to collect these data were not available. Finally, because all subjects were women, the present results may not reliably be extrapolated to men.

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