The Variable Component of Lateral Body Sway During Walking in Young And Older Humans

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Introduction. Because sideways falls are common in elderly persons, we devised a method to measure variable lateral movements of the thorax with respect to foot position during normal walking.

Methods. Movements of the ankles and shoulders were measured during walking a distance of 9 m. Two age groups were studied: young (n = 17, 6 male, mean age 27.3 years) and older (n = 21, 13 male, mean age 72.7 years) people. During walking, the path followed in the horizontal plane by the midpoint between the two shoulders was compared to the line connecting successive positions of the ankles during stance. Lateral deviations between these two paths were divided into a regular component (average of about 30 strides) and a variable component (the difference between the deviation during each stride and the average). Lateral sway was also observed while standing with eyes open for 1 minute.

Results. The older group had more lateral movement during walking in the variable component (p = .006) and a nonsignificant trend (p = .054) in the same direction in the regular component. Eight of the older participants had a value for the variable component greater than the 95% confidence limit for the young participants. Only two of the older participants had a standing sway outside the confidence limit for the young participants. The variable component was associated with variability in stride width.

Discussion. The variable component of lateral sway during walking provides good discrimination between age groups, as does variability in step width. It remains to be seen whether these variables are different in fallers and nonfallers.

Walking is an inherently unstable activity. The body is in a single support phase for 80% of the time, during which its center of gravity falls outside the confines of the stance foot (1). Furthermore, the center of gravity is located 2/3 of the body height above the ground and therefore represents a large inertial load to be controlled (2). The success of this control during walking can be estimated if the movements are divided into a regular component, which repeats with each stride, and a residual, or variable, component that would be negligible if control were perfect.

Variable movements during walking have been relatively little studied compared with those during standing. The latter are well known to be associated with both ageing (3–5) and with falling frequency (6–9). Many falls, however, occur during walking (6,10–14). An additional requirement for a safe gait is an accurately controlled foot trajectory during the swing phase of the gait cycle.

Stride-to-stride variability in a number of parameters of gait (speed, cadence, step length, stride time, double support time, stance time) have been shown to be positively associated with falling in older persons (15–19). Maki (19), however, found that decreased variability in step width was predictive of falling during walking.

In this article we have studied both the regular and the variable lateral movements of the thorax during walking in two age groups of healthy persons, and have compared these with the sway during standing.

METHODS

Participants

The older participants were recruited through an advertisement in local newspapers. They were living independently in the community and reported falling no more than once during the previous year and therefore were classified as “nonfallers” (20). The young participants were colleagues and university students. All participants were naive as to the experimental hypotheses to be tested. Participants completed a medical questionnaire adapted from that of Greig and colleagues (21), which included questions about regular physical activity. Only those persons considered ‘healthy’ using their criteria and regularly undertaking at least mild exercise (walking for more than 0.5 hour per week) were admitted to the study. Exclusion criteria were an inability to walk without an assistive device and any musculoskeletal, neurological, or vestibular dysfunction revealed by the questionnaire which, in the opinion of a senior geriatrician, was likely to either impair standing or walking or increase sway. All participants gave written informed consent to participate in the study, which had the approval of the ethics committee of the Royal National Orthopaedic Hospital Trust and was carried out in accordance with the Declaration of Helsinki. Characteristics of the two participant groups (means ± SEM) are given in Table 1.

Motion Analysis

The CODA MPX30 system was used (Charnwood Dynamics, Leicestershire, U.K.). This system monitors the
position of markers, which are infrared light-emitting diodes attached to the participant’s body. The measurements were made by a base station placed in front of the participant. This station signals the markers when to flash and measures the position of each marker 100 times per second. Within the space observed, which is 6 m \( \times \) 2 m \( \times \) 2 m, the precision of the measurement of movement is 0.7 mm in the y-axis (to/from the base station) and 0.5 mm in both the vertical z-axis and the orthogonal x-axis. The accuracy of the system was checked by observing a grid of markers placed at known positions. The maximum error within the region used in this experiment was 0.4 mm.

**Experimental Protocol**

The participants were barefoot and wore shorts and a close-fitting T-shirt. The level floor was covered by a thin carpet. Very light (10 g) markers were attached bilaterally by double-sided tape to the skin or clothing.

Standing stability was measured over an approximately 8 m distance with participants being asked to walk at their preferred speed along a 15 m path toward a fixed point. Each participant performed four to six walks. The CODA was mounted 2.5 m above the floor looking downward at an angle of 10°. The participants walked towards the CODA and passed underneath it. Four markers were placed over the medial malleoli and the coracoid processes of the scapulae.

Standing stability was measured over three 1-minute periods during which the participants were asked to stand as still as possible with their eyes open. They were positioned 3 m in front of the CODA, which was mounted at a height of 0.8 m. Their foot positions were not constrained in any direction. In addition to the four markers used for the walking analyses, eight more markers were used at the following positions bilaterally: patella, anterior superior iliac spine (ASIS), temporomandibular joint (TMJ), and the lateral aspect of the orbit.

**Data Analysis**

The co-ordinate data from the CODA system were rotated so that the y-axis was parallel to the line of progression and the z-axis vertical. These rotations were necessary because of the mounting position and angle of the CODA. Data for the first 1 m and last 2 m of each walk (which was out of view of the CODA) were rejected. The number of steps taken in these sections of each walk was not measured. In addition, we rejected any steps during which more than 50% of the marker measurements were unsuccessful, because insufficient light reached the detectors from the marker. This occurred only at either the start or end of the walk when the ankle markers were out of view of the camera. We did not analyze records when markers were lost by being obscured by other parts of the body when the participants were walking in view of the camera. At least 25 (range 25–60) measurements of each marker were required for a step to be used. The average number of steps analyzed from each participant was 34 and varied with the total length of the walk in view of the camera and the individual’s step length.

A virtual marker was created midway between the two coracoid process markers and 68 mm posterior to them, to be close to the center of the thorax. Measurements were relatively insensitive to small changes in the position of this virtual marker (difference of 20 mm resulted in a 4% difference in the amplitude of the variable component of lateral sway). Crossing points were identified, using the height of the ankle markers, to indicate the start and end of each individual gait cycle. Each foot was said to be in the support phase when the ankle was lower than the contralateral ankle. The ankle marker position was averaged for the central 0.1 second of each support phase, providing a series of footfall positions. Straight lines connecting subsequent footfalls in the horizontal plane represented the approximate path that the thorax might be expected to follow. The actual path of the thorax marker was compared with this series of straight line segments, and the difference represented the lateral error signal to be analyzed. Step width was calculated as the lateral difference between successive footfall positions found in this way.

Analysis of the standing data was carried out by first subtracting from the position data for each marker the mean position during the whole 1-minute record. For each time point the mediolateral movement of each marker was plotted against its mean height and a regression line was fitted to the plot. The slope of this line gave for each time point the angular displacement of the body (mrads) from its mean orientation. The standard deviation of these values for each participant is reported as the index of standing sway. All calculations were performed using Mathcad 2001 Professional software (MathSoft Engineering & Education, Inc., Cambridge, MA).

**Statistics**

Differences between groups were investigated using repeated measures two-way analysis of variance with age and sex as factors. Pearson product moment correlation and linear regression were used to examine relationships between sway and either age or body mass index (BMI). A significance level of 5% was used. Data are presented as mean ± SEM.

**RESULTS**

A typical set of recordings from one older participant of the path followed by the feet and the thorax in four walks is
shown in Figure 1. The broken line is the path obtained by joining the positions of the ankles in each successive support period. The full line is the actual path followed by the thorax. At each time point, the deviation in the mediolateral direction between actual and straight lines connecting the footfalls (which we call the total lateral sway) was calculated. These values for all strides used (from four to six walks) are plotted against fraction of stride time in Figure 2. The mean of all these strides represents the regular component of the sway (thick line). This was used to construct a regular sway pattern, taking due account of the timing of each stride, for comparison with the observed record from each walk (Figure 3). The difference between the actual sway path and the regular path is the variable component of the sway. The regular and variable components were quantified by calculation of their root mean squared (RMS) values.

Age and Sway During Walking

The older participants had a greater total lateral sway (14.1 ± 0.7 mm; \( p < .001 \)) than the young participants (10.8 ± 0.6 mm). The variable and regular components are shown as a function of age and sex in Figure 4, and the group mean values are in Table 2 together with other gait parameters. It can be seen that the increase in sway in the older group was largely due to the increased variable component (10.2 ± 0.5 mm vs 7.4 ± 0.3 mm; \( p = .0006 \)). The regular error component made only a smaller and nonsignificant contribution to the observed age difference (9.5 ± 0.6 mm vs 7.5 ± 0.7 mm; \( p = .054 \)).

There was a nonsignificant tendency for the men to have a larger variable component than the women (\( p = .016 \)) but there was no significant difference in the regular component (\( p > .05 \)). The analysis of variance gave no significant interactions between age and sex for any variable. Because there was a significantly greater BMI in the older participant group (Table 1), we tested (by multiple regression with age and BMI as independent variables) whether BMI influenced sway. No significant effects were found.

Variability of Gait Pattern

Table 2 compares the absolute values and variability of step length, width, and time for each participant group. The step lengths, widths, and times were similar for the two groups but there was significantly more variability in the older group for both step length and step width. There was a strong correlation (\( r = 0.808, p < .0001 \)) between the step width variability and the variable component of sway during walking (Figure 5). However, there was no correlation between step width and any component of sway. Walking speed was similar in both groups.

Lateral Sway During Walking and Standing

The older participants had a greater lateral sway while standing than did the young participants (3.0 ± 0.2 vs
2.4 ± 0.2; p < .05) (Table 2). The difference between groups in variable lateral sway during walking was larger than that during standing in both absolute and relative terms. There were only two older participants whose sway while standing was outside the 95% confidence limits for the young participants (see Figure 6). In contrast, there were eight older participants whose variable sway while walking was outside the corresponding limits for the young participants. Taking all the participants together there was a significant correlation (p < .01) between sway during walking and sway during standing. However, within each age group these two variables were not significantly correlated.

**DISCUSSION**

These data indicate that the age-related increase in lateral sway during gait is due to an increase in both the variable and regular components of sway. The variable component is more affected by age in terms of amplitude and consistency.

Most studies of balance measure movements in the anterior-posterior direction, or include a global measure that does not distinguish between the two directions and is dominated by the larger anterior-posterior movements. However, there is strong evidence that lateral balance is of prime importance. Impairments of balance due to both age and pathology are reported to be more obvious in the lateral direction (22,23), and measurements of lateral balance have also been claimed to be better predictors of the risk of falling (24,25). Many falls in elderly persons are in the lateral direction (26,27). These are particularly important as this is the fall

![Figure 4](image-url) Components of sway plotted against age for men (closed symbols) and women (open symbols). Horizontal bars = mean values for the men (solid lines) and women (dotted lines). RMS = root mean squared.

![Figure 5](image-url) Step width variability and the variable sway component were highly correlated in the older participants (closed symbols; r = 0.840) but not in the younger participants (open symbols; r = 0.381).

### Table 2. Gait Characteristics and Sway in the Two Age Groups

Presented as Mean (SEM)

<table>
<thead>
<tr>
<th>Gait Characteristics and Sway</th>
<th>Old (N = 21)</th>
<th>Young (N = 17)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step time, ms</td>
<td>565.8 (14.8)</td>
<td>546.0 (8.8)</td>
<td>.26</td>
</tr>
<tr>
<td>Step time variability, ms</td>
<td>51.1 (6.4)</td>
<td>44.1 (4.5)</td>
<td>.37</td>
</tr>
<tr>
<td>Step length, mm</td>
<td>620.2 (19.4)</td>
<td>644.2 (9.8)</td>
<td>.29</td>
</tr>
<tr>
<td>Step length variability, mm</td>
<td>36.7 (2.7)</td>
<td>28.5 (2.1)</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Step width, mm</td>
<td>115.5 (3.9)</td>
<td>118.3 (5.6)</td>
<td>.68</td>
</tr>
<tr>
<td>Step width variability, mm</td>
<td>23.2 (0.6)</td>
<td>17.3 (0.9)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Total lateral sway, mm</td>
<td>14.0 (0.71)</td>
<td>8.5 (0.59)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Regular lateral sway, mm</td>
<td>9.5 (0.52)</td>
<td>7.4 (0.32)</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Variable lateral sway, mm</td>
<td>10.1 (0.52)</td>
<td>7.4 (0.32)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Standing sway, mrad</td>
<td>3.0 (0.19)</td>
<td>2.4 (0.21)</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>Walking speed, m/s</td>
<td>1.12 (0.06)</td>
<td>1.19 (0.03)</td>
<td>.32</td>
</tr>
</tbody>
</table>

*Note: Although the absolute gait characteristics were similar, the older participants had greater variability in step length and width and also more variable sway.*
direction most associated with hip fracture (28–30) and the well documented associated consequences of this injury.

The variability in the walking pattern within one individual has been studied at least since the work of Gabell and Nayak (16). Recent work has continued to be based on the measures they introduced: step length, step width, and stride time (18,19,31,32). It has been found that older individuals have more variability in stride width and length (16,18,31–33), and in some cases step timing (34), than do younger individuals. The increased variability of stride width in older people could be related to reduced stability, because it might result from the feet being inappropriately placed to accept the load from the moving center of mass as it passes forward. We have investigated this possibility by simultaneously monitoring and comparing the lateral position of the thorax and of the feet. Our measures of mean stance width agree with those of others (16,18,19,31,32). Although Gabell and Nayak (16) did not find a significant increase in step width variability with age, their median results do show a trend in this direction about as large as the statistically significant effect that we report.

Previous work has concentrated on the characteristics of the steps performed, rather than on balance or sway directly, although it is recognized that they are an important predictor for falling in elderly persons. More recently, acceleration has been used to monitor movement of different parts of the body in all three axes. Menz and colleagues (34) reported that older persons generally showed less acceleration at both the head and pelvis. However, the mediolateral acceleration of the head was significantly greater in the older group. This is compatible with our finding of increased lateral motion. It is notable that the absolute measurements of step time and length, as well as step time variability, were similar in the two groups, whereas they were clearly distinguishable on the basis of variability in step width and length (Table 2). We suggest that direct measures of sway are valid and important and, as indicated by the data presented here, should be separated into regular and variable components. Maki and colleagues (35) studied the effects on lateral balance of a perturbation during walking in healthy young and old people. The older persons were much more likely to take additional steps and to move the arms for counterbalancing.

The mechanisms underlying the increased variable lateral sway are currently unknown and are likely to be multifactorial. One possibility is that the older persons are less able to sense the regular path, perhaps because of the age-related decline in joint proprioception (36,37) or other age-related changes in the musculoskeletal, motor, and sensory neural systems.

The strong correlation ($r = 0.808$) between the variable lateral sway and variability in step width in the older group is striking, particularly with the relatively small numbers of individuals studied here. It might mean that both parameters are measuring different aspects of the same phenomena or alternatively one may be the consequence of the other. One possible scenario is that foot placement becomes less regular in the older participants, making it more difficult for the thorax to follow the foot placement pattern. Equally possible is the opposite, where thoracic movement becomes less stable and foot placement is an attempt to compensate for thoracic movement and maintain stability. In both cases the result is an increased demand on the systems involved in muscular control and performance, and the ageing system may not be able to meet the requirements. Studies involving greater numbers of persons over a spectrum of ages, rather than the two age-separated groups studied here (age-matched fallers and nonfallers), and also intervention studies involving gait perturbation might be informative in this respect.

The difference between the age groups for the variable component of lateral sway is particularly striking in view of the fact that the group of older participants were active, healthy people who did not have a history of falls. It remains to be seen whether the lateral sway patterns differ in age-matched older people who do and do not fall regularly and, if so, whether differences are found predominantly in variable or regular components.

Perhaps surprisingly, the amount of lateral sway during standing was not a particularly good indicator of that during walking (Figure 6). Different individuals showed the most sway in the two tests. Walking sway, although more difficult to measure, is of greater functional importance. Measurements of the variable component during walking appeared to be more sensitive as more of the older group were outside the limits of the younger group.

There seem to be strong arguments for measuring these parameters of lateral sway in studies of falls and ageing and, in particular, for finding out whether an increase in the variable component is predictive of falls. In this connection it is important to note the surprising results of Maki (19), who has shown that a decrease in step width variability is predictive of falling. If a clear relationship can be shown between
falling and either step width variability or the variable component of lateral sway then the corresponding measurement could be of value in the management of individual patients. The analysis performed in this study required relatively few motion analysis markers during data collection, but data analysis was complicated and time consuming. If, as seems likely, comparable information can be obtained by variability in step width, then simple apparatus and data processing suitable for a clinical setting would be possible. It also remains to be seen whether the increased lateral sway can be improved by physical or other interventions.

ACKNOWLEDGMENTS

Dr. Birles is now with the Department of Psychology, University College London, United Kingdom.

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