Journal of Gerontology: MEDICAL SCIENCES
2001, Vol. 56A, No. 7, M438–M447

Trunk Sway Measures of Postural Stability During Clinical Balance Tests: Effects of Age

J. Gill,[1] J. H. J. Allum,[1] M. G. Carpenter,[1,2] M. Held-Ziolkowska,[3] A. L. Adkin,[1,2] F. Honegger,[1] and K. Pierchala[3]

[1]Department of Otorhinolaryngology, University Hospital, Basel, Switzerland.
[2]Department of Kinesiology, University of Waterloo, Ontario, Canada.
[3]Department of Otorhinolaryngology, Medical University of Warsaw, Poland.

Background. The major disadvantage of current clinical tests that screen for balance disorders is a reliance on an examiner's subjective assessment of equilibrium control. To overcome this disadvantage we investigated, using quantified measures of trunk sway, age-related differences of normal subjects for commonly used clinical balance tests.

Methods. Three age groups were tested: young (15–25 years; $n = 48$), middle-aged (45–55 years; $n = 50$) and elderly (65–75 years; $n = 49$). Each subject performed a series of fourteen tasks similar to those included in the Tinetti and Clinical Test of Sensory Interaction in Balance protocols. The test battery comprised stance and gait tasks performed under normal, altered visual (eyes closed), and altered proprioceptive (foam support surface) conditions. Quantification of trunk sway was performed using a system that measured trunk angular velocity and position in the roll (lateral) and pitch (fore-aft) planes at the level of the lower back. Ranges of sway amplitude and velocity were examined for age-differences with ANOVA techniques.

Results. A comparison between age groups showed several differences. Elderly subjects were distinguished from both middle-aged and young subjects by the range of trunk angular sway and angular velocity because both were greater in roll and pitch planes for stance and stance-related tasks (tandem walking). The most significant age group differences ($F = 30$, $p < .0001$) were found for standing on one leg on a normal floor or on a foam support surface with eyes open. Next in significance was walking eight tandem steps on a normal floor ($F = 13$, $p < .0001$). For gait tasks, such as walking five steps while rotating or pitching the head or with eyes closed, pitch and roll velocity ranges were influenced by age with middle-aged subjects showing the smallest ranges followed by elderly subjects and then young subjects ($F = 12$, $p < .0001$). Walking over a set of low barriers also yielded significant differences between age groups for duration and angular sway. In contrast, task duration was the only variable significantly influenced when walking up and down a set of stairs. An interesting finding for all tasks was the different spread of values for each population. Population distributions were skewed for all ages and broadened with age.

Conclusions. Accurate measurement of trunk angular sway during stance and gait tasks provides a simple way of reliably measuring changes in balance stability with age and could prove useful when screening for balance disorders of those prone to fall.

THE high incidence of serious falls among elderly people has prompted many researchers to investigate age-related changes in postural control. Research in this area has indicated that aging has detrimental effects on postural control, which cause an increase in body sway (1–3). Despite the variety of laboratory methods and clinical tests to describe instabilities in stance and gait, there is still a need for screening, assessment, and monitoring protocols that combine quantitative evaluation with ease of administration (4).

Different balance control mechanisms for standing and gait have been supported by low correlations between clinical stance and locomotor tasks (5). Therefore, clinical balance protocols should incorporate a range of tasks that requires balance performance under both static postural locomotor conditions. Postural instability associated with age and a number of balance disorders typically stem from a deterioration or failure of peripheral sensory systems. Therefore, it seems essential for an effective balance screening protocol to include tasks that isolate or target the use of particular sensory systems.

Current clinical tests (6–14) are often restricted to narrow areas of postural control such as the ability to perform functional tasks within physical limitations or sensory contributions to balance control. These tests are not complicated but are primarily qualitative because they rely on the administrator's subjective evaluation (3). The balance tests that have been developed for clinical use implement a variety of different measurement techniques. Often, these tests use a binary classification, which may help to distinguish between normal and pathological performance but which is not focused on detecting changes over time or on the extent or source of an impairment. A common method employed is to time different movements or to measure the duration that specific postures are maintained (6–10). Time measurements are useful because velocity influences the challenge imposed on balance control (3) and because increased task duration could reflect a change in the subject's perceived or actual functional limits of sway velocity stability, assuming the same amplitude of sway was required for the task. Thapa's (11) analysis of balance tests revealed that five timed walking tests showed poor gait performance to be associated with falling. There are also several tests of functional ability (7,12–14) that use ordinal scales to classify general balance performance into broad categories of normal or abnormal. These clinical balance tests provide information on an individual's ability to control balance but are generally insufficient on their own. These evaluations examine limited aspects of balance control and do not provide complete screening or diagnostic information. A possibility of inconsistent scoring also arises because the evaluations are subjective. Additionally, because the tests are tuned to a binary scale, the tests are built around a fail-pass concept rather than a range of instability.

Examples of widely used tasks that have the restrictions mentioned above are Tinetti's Performance Oriented Assessment of Mobility (12) and the Clinical Test of Sensory Interaction in Balance (CTSIB) devised by Shumway-Cook and Horak (6). However, these tests can be adapted for quantitative measurement of trunk sway and were therefore used to guide the development of our protocol. Tinetti's (12) test was the first test to incorporate both gait and stance balance measures. Its goal is to predict the risk of falls in elderly subjects by having them perform a variety of functional tasks that examine various aspects of balance control (15,16). The test is quick and simple to administer (16), although there is debate over its ability to detect changes in the case of borderline pathology (15,16) because it simply establishes the presence or absence of a balance disorder. Thus, once a balance disorder is discovered, further quantified examination is required to determine the possible causes (15). According to Horak (17), the Tinetti protocol has only moderate predictive accuracy and poor sensitivity.

The CTSIB developed by Shumway-Cook and Horak (6) is a comprehensive evaluation of the sensory contributions to balance control. It was developed to overcome the shortcomings of the Tinetti protocol and considers a variety of sensory conditions and postures that one may encounter during normal daily activities; therefore, it provides a more complete picture from which to predict the risk of falling. Its purpose is to determine the roles of visual, somatosensory, and vestibular inputs through the evaluation of stance under normal and altered sensory conditions (15–17). A time scale is used to measure the duration of performance (6). Although the CTSIB has proven reliable and valid (16–18) and sensitive to deterioration in performance with age (15,18), there are major drawbacks associated with this test battery. One drawback is the reliance on timing alone. Two subjects could stand for the maximum test duration of 30 seconds but could differ widely in sway amplitudes. El-Kashlan and colleagues (15) found the CTSIB test to be significantly less sensitive to subtle patterns of motor dysfunction and biased toward diagnosing abnormalities such as peripheral vestibular loss. These authors suggested that a simple CTSIB evaluation would produce false negatives in 40% of the total cases. Also, the CTSIB attempts to measure only the sensory aspect of balance primarily under stance conditions. This limits its external validity given that most falls are the result of unexpected conditions encountered during gait activities (3,5,19,20).

Laboratory video-based techniques (5,15) and strain-gauge–based posturography platforms (21,22) provide quantitative measurement of postural control. However, they are impractical as a general screening tool. Such laboratory measures, which involve biomechanical evaluation, are both time consuming and expensive. As well, these systems are generally not portable and require specially trained personnel, which makes their use unavailable to the average clinician requiring balance screening. However, posturography platforms have proved useful in identifying excessive lateral sway during quiet stance as a predictor of falls (20).

It is clear from the above discussion that a more sensitive and quantitative screening test for balance deficits in elderly persons is required that maintains the simplicity of administration offered by currently available clinical tests. The protocol of our study was developed to address the problems of the clinical evaluation methods presently available. We used a light-weight device that measures trunk angular velocity while the subject performs a variety of tasks. This provides a screening method that bridges the gap between subjective clinical evaluation and dynamic platform posturography (21,22). Our goal was to determine the efficacy of this new device as a postural assessment tool for elderly persons and to establish normal age-related quantitative values of trunk sway for parts of the CTSIB and Tinetti protocols. The variety of tasks included in our protocol covers different situations of balance control including maintenance of stable posture, balance during gait, and reaction to external stresses that meet the three criteria outlined by Berg (3) for balance control screening. The component tasks of the protocol and the use of angular velocity transducers provide a systematic balance evaluation with quantified measures of trunk sway.

Methods

Subjects

Young (15–25 years, $n = 48$), middle-aged (45–55 years, $n = 50$), and elderly (65–75 years, $n = 49$) subjects participated in this study. There were equal numbers of men and women in each age group, except that the elderly group had 1 more male subject ($n = 49$). On the basis of self-report and the clinical test observations of the authors, all subjects were free of any known disorder that could influence balance control, including musculoskeletal, vestibular, or somatosensory disorders. Each subject provided witnessed informed consent prior to participating in the experiment.

Procedure and Apparatus

The trunk sway measuring device consisted of two angular-velocity transducers mounted on the plastic molding of an adjustable, partially elasticized, motorcycle kidney belt (Sway Star, developed with Nicolet Biomedical Inc, Madison, WI). Subjects wore the belt inverted to position the sensors in the lumbar region of the back. The transducers were oriented such that one measured angular velocity deviations in the roll (side-to-side) plane and the other measured angular velocity in the pitch (fore-aft) plane. Samples of angular velocity in the range ±327°/s were sampled at 100 Hz. Angular deviations were calculated on-line using trapezoid integration of the angular velocities and displayed with angular

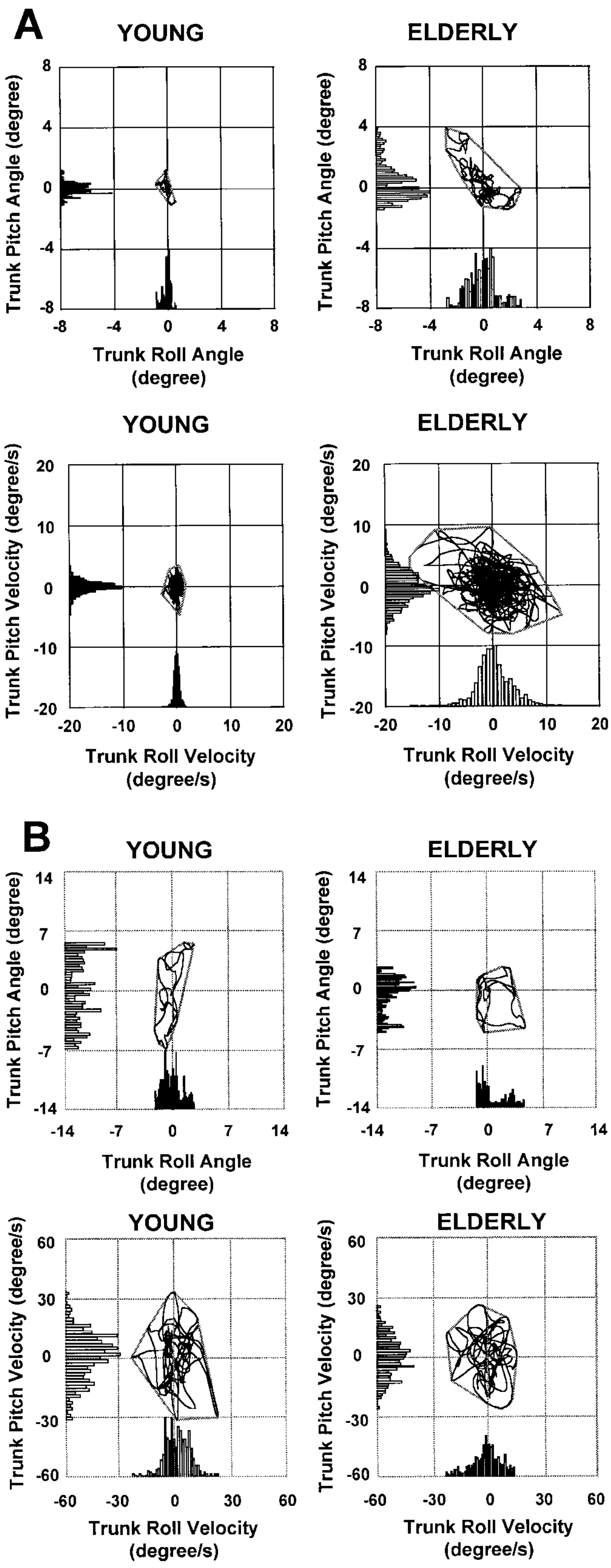

Figure 1. Typical examples of roll and pitch trunk sway recorded from a young subject (left set of plots) and an elderly subject (right set of plots). **A**, Standing on one leg with eyes open; **B**, walking five steps while pitching the head up and down. Angular displacement or velocity is plotted in each diagram with pitch along the vertical axis, and roll is plotted along the horizontal axis. Rightward roll and backward pitch is plotted positive. Distributions of the samples are shown along the axes. The envelope of the recordings (the convex hull) is also shown. Note the increase in sway in the roll and pitch direction for the stance task in the elderly subjects but the decrease in pitch for the gait task compared with the young subjects.

Table 1. List of Stance and Gait Tasks

Stance Tasks
Standing on two legs with eyes open
Standing on two legs with eyes open on foam support
Standing on two legs with eyes closed
Standing on two legs with eyes closed on foam support
Standing on one leg with eyes open
Standing on one leg with eyes closed
Standing on one leg with eyes open on foam support
Stance-related Tasks
Walking eight tandem steps
Walking eight tandem steps on foam support
Gait Tasks
Walking five steps with eyes closed
Walking five steps while horizontally rotating the head
Walking five steps while vertically pitching the head
Walking over barriers
Walking up and down stairs

velocity as x-y plots (see Figure 1). Because the baseline drift of the device is specified as less than 36 degrees/h or 0.01 degrees/s (1 *SD*) and our maximum measurement interval was 20 seconds, inherent drift in our integrated position recording was less than 0.2 degrees. Furthermore, samples of angular velocity were taken with 16-bit resolution with 1 bit equivalent to 0.005 degrees/s, that is, below the level of inherent transducer drift. The complete test protocol involved fourteen different tasks (see Table 1). Stance tasks examined subjects standing on one and two legs with eyes open and closed on normal and foam support. Stance-related tasks included walking eight tandem steps on normal and foam support. Gait tasks involved walking 5 steps with the eyes open while rotating and pitching the head and with eyes closed (without head movements), as well as walking over barriers and up and down a set of stairs. The foam support surface was 10 cm thick and 44 cm wide by 204 cm long. The four barriers used (3-by-3-cm wooden slats) were placed at a height of 0.24 m above the ground and spaced 1 m apart. A set of stairs, with two upward and two downward steps (step height = 0.23 m) and without handrails, was used.

All trials were performed without shoes to avoid the effect of different shoe types (heels or not, for example) entering the data. For two-legged stance tasks, subjects were instructed to assume a normal, comfortable standing position with the arms at the sides and to stand quietly for 20 seconds. For one-legged trials, subjects were not allowed to stabilize their raised leg against their standing or support leg. The one-legged stance tasks were also performed for a maximum duration of 20 seconds. Data collection was immediately stopped in the case of a loss of balance. A trial was repeated once if the patient lost balance within 20 seconds, and the longest trial was used for analysis. Gait trials were self-paced with duration defined as the time to complete the task. For the tasks involving head pitching and rotating, head movements were performed in synchrony with step cadence. For all tasks, at least one spotter stood close to the subject to provide assistance if a loss of balance occurred.

Data Analysis

The first second of recorded data was not included in the analysis to eliminate initial balance stabilizing movements. Such movements were especially prevalent for one-legged tasks because subjects always achieved a stable position slightly different from their original two-legged stance position. The last 2 seconds were eliminated from the stance tasks to prevent the effects of a loss of balance from entering the data analysis. Duration was set as the total trial length.

Data analysis consisted of measuring the range of pitch and roll angular displacement and velocity. The range was measured in two ways. The first method used the peak-to-peak extent of the values for the task in the roll and pitch directions following removal of the first second and, for stance trials, the last 2 seconds of the trial. The second method involved binning all samples for the trial to accumulate a histogram of pitch and roll angular displacement and velocity values (see Figure 1). From these histograms, 5% and 95% limits were calculated, and the extent of these limits was assigned to a 90% range value. Our statistical analysis showed the same significant differences for age between populations with these two measurement methods. Therefore, we will report only the analysis performed on peak-to-peak measurements.

The distribution of peak-to-peak measurements within each age group was more Poisson-like than Gaussian (normal) as illustrated in Figure 2. For this reason both nonparametric and parametric analyses were performed on the data. The cumulative amplitude distributions of the peak-to-peak measurements were examined using the nonparametric Kolmogarov-Smirnow test, which tests the degree of agreement between distributions. For this test, significance was set at $p < .05$.The data were then log-transformed to provide a more Gaussian-like distribution prior to parametric statistical analysis. To determine if age-related differences were present in the data, a one-way analysis of variance (ANOVA) was performed on the five dependent variables (roll and pitch angular range, roll and pitch angular velocity range, and duration) for each of the fourteen tasks. ANOVA were also performed to examine differences between tasks within a group of similar tasks, for example, two-legged stance tasks, and between genders. Following the determination of a significant main effect of age and test condition, significant differences between age groups for each variable were explored with Bonferroni *t* tests. For the Bonferroni tests, minimum significance was set at $p < .05$. Because three pairs of populations means were considered for each test, a single paired comparison required a *p* value less than .0167 to be significant.

Results

Comparisons between age groups showed significant results for all five measurement variables in most tasks (see Figures 2–7). The age effect that achieved significance differed depending on which task was performed.

Trunk Sway Amplitude Distribution Patterns

The elderly subjects did not exhibit greater sway than the young subjects for every task; for some tasks, the elderly subjects swayed less than the young subjects. For example, Figure 1 shows the x-y plots of a typical subject from each of the young and elderly populations. The roll sway angle and angular velocity for the one-legged stance task (Figure 1A) is clearly greater in the elderly subject. In contrast, the pitch angle and angular velocity for the gait task of walking while pitching the head (Figure 1B) is smaller for the elderly subject. Thus, the sign or direction of the difference

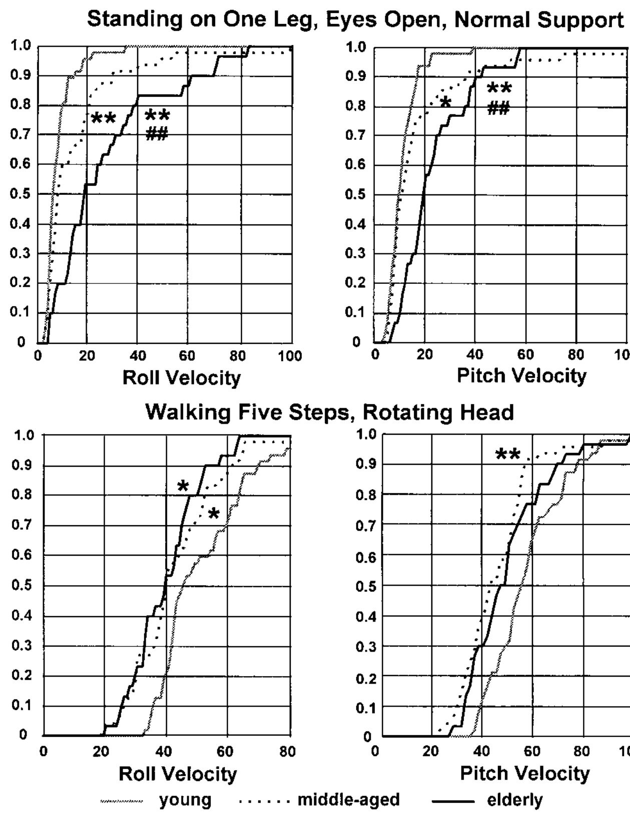

Figure 2. Cumulative amplitude distributions of values of roll and pitch angular velocities for the tasks of standing on one leg with eyes open and walking five steps while rotating the head for the young, middle-aged, and elderly populations. The abscissa is the peak-to-peak amplitude of roll or pitch velocity for each subject's sway. The ordinate is the percentage of subjects in the group with sway amplitude below the value along the abscissa. Thus, for standing on one leg with eyes open only 53% of the elderly subjects had amplitudes less than 20 degrees/s, whereas 95% of the young subjects sway this amount or less. Significant differences between the distributions determined by the Kolmogarov-Smirnov test are indicated. Notice the different age ordering of the distributions between the stance and gait tests. *$p < .05$ for elderly and middle-aged compared with young; #$p < .05$ for elderly compared with middle-aged; **$p < .01$ for elderly and middle-aged compared with young; ##$p < .01$ for elderly compared with middle-aged.

Table 2. Significant *F* Statistics and Associated *p* Values Observed When Testing for Differences Between Selected Stance, Stance-Related, and Gait Tasks

Tasks Compared	Duration	Roll Angle	Pitch Angle	Roll Velocity	Pitch Velocity
s2eo, s2ec, s2eom, s2ecm	–	175.99 (.0001)	95.58 (.0001)	277.68 (.0001)	151.89 (.0001)
s1ec, s1eo	–	–	–	–	–
s1eo, s1eom	–	64.29 (.0001)	19.25 (.0001)	87.94 (.0001)	38.94 (.0001)
w8tan, w8tanm	–	–	102.09 (.0001)	94.96 (.0001)	72.60 (.0001)
w5ec, w5hp, w5hr	–	15.18 (.0001)	11.61 (.0001)	–	16.14 (.0001)

Note: s2eo = standing on two legs with eyes open; s2ec = standing on two legs with eyes closed; s2eom = standing on two legs with eyes open on foam support; s2ecm = standing on two legs with eyes closed on foam support; s1ec = standing on one leg with eyes closed; s1eo = standing on one leg with eyes open; s1eom = standing on one leg with eyes open on foam support; w8tan = walking eight tandem steps; w8tanm = walking eight tandem steps on foam support; w5ec = walking five steps with eyes closed; w5hp = walking five steps while vertically pitching the head; w5hr = walking five steps while horizontally rotating the head.

between the mean values of the young and elderly population sway measures varied between stance and gait tasks. In addition, the shape of the distributions varied with age and between tasks as shown in Figure 2. The upper part of Figure 2 shows cumulative amplitude distributions for the range of angular velocity measured during the one-legged eyes-open stance. The distributions depicted in the figure are typical of those of one- and two-legged stance tasks as well as the stance-related task of tandem walking. These distributions show that most values for the young subjects are clustered around a narrow range. The values for the middle-aged and elderly subjects are distributed over a wider range, although some of the elderly subjects had values equal to those of the most stable middle-aged and young subjects. A distinct change in the pattern of these distributions was observed for the gait tasks as shown in the lower part of Figure 2. Here, the order of sway amplitude is changed between the young and elderly subjects with the young subjects in general demonstrating more sway. Furthermore, instead of the distributions starting at the same point and having a different range of values as in the upper part of Figure 2, the cumulative distributions are simply shifted between age groups for the gait tasks. Our statistical tests of age-related differences of nonparametric tests of significance as shown in Figure 2 were confirmed with parametric tests (Figures 3–7).

Two-Legged Stance Tasks

For two-legged stance tasks, all four sway and velocity measures increased in range as the task became more difficult as sensory information was changed (i.e., eyes open normal support was less than that with eyes closed normal support which was less than that for eyes open on foam support and for eyes closed on foam support; see Table 2). All four two-legged tasks also showed a significant increase in range of roll and pitch angle as age increased, except roll velocity on the foam support and pitch velocity eyes open on foam support (Figure 3). Interestingly, the influence of age on sway angle and velocity during two-legged stance was dependent upon the task and therefore upon the amount of sensory information available. Elderly subjects had significantly higher roll and pitch angular sway amplitude values than young subjects for all four two-legged tasks. Compared with the middle-aged subjects, the elderly subjects

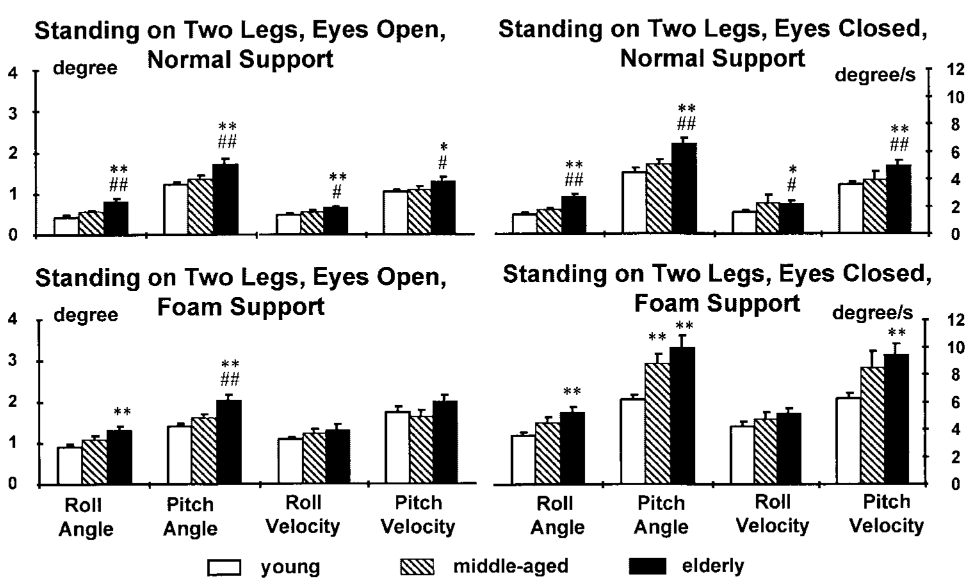

Figure 3. Increase of population trunk sway means with age for two-legged stance tasks. The columns have a height equal to the mean value for the population. Standard errors of the means are indicated by vertical bars on the tops of the columns. Ordinate scales for trunk sway angle are on the left, and ordinate scales for trunk sway angular velocity are on the right of the figure. Significant differences between the means after logarithmic transformation of the data as determined by Bonferroni *t* tests are indicated. *$p < .05$ for elderly and middle-aged compared with young; #$p < .05$ for elderly compared with middle-aged; **$p < .01$ for elderly and middle-aged compared with young; ##$p < .01$ for elderly compared with middle-aged.

had significantly higher pitch and roll angle when standing with eyes open and closed on normal floor, and for pitch angle sway only when standing with eyes open on foam support. There was no significant difference between elderly and middle-aged subjects when standing with eyes closed on foam support. Sway velocity followed a similar trend as sway angle measures because the elderly subjects had significantly higher velocity ranges in pitch and roll planes compared with both young and middle-aged subjects for both eyes open and eyes closed conditions on normal floor. There were no significant differences between groups for pitch or roll velocity measures when standing on foam support, except for significantly higher pitch velocity in elderly compared with young subjects during eyes closed on foam support. For all two-legged stance conditions the young and middle-aged groups performed similarly, with the exception of standing with eyes closed on foam support, for which the middle-aged subjects demonstrated significantly larger pitch sway angle than young subjects (Figure 3).

One-Legged Stance Tasks

Standing on one leg, not surprisingly, caused a dramatic increase in sway compared with two-legged stance. Sway on one leg with eyes open showed a highly significant difference with age. Figure 4 illustrates the change with age for a normal and foam support surface. Similar to two-legged stance tasks, the influence of age on trunk pitch and roll

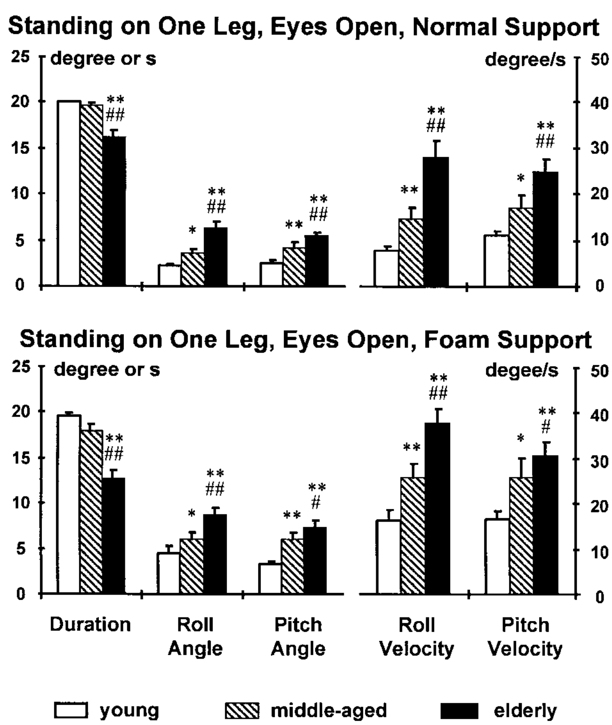

Figure 4. Means of sway measures in young, middle-aged, and elderly subjects for one-legged stance tasks. Note the increase in all sway angle measures and the decrease in time before balance terminated (duration) with age. *$p < .05$ for elderly and middle-aged compared with young; #$p < .05$ for elderly compared with middle-aged; **$p < .01$ for elderly and middle-aged compared with young; ##$p < .01$ for elderly compared with middle-aged.

sway angle and sway velocity was dependent upon the sensory information available. All sway values of the elderly subjects recorded with eyes open were significantly greater than those of the younger populations, and sway values of the middle-aged subjects were significantly greater than those of the young subjects. Stance duration was also significantly different between populations. The duration of stance was significantly shorter for the elderly subjects compared with the young and middle-aged subjects. Stance duration values for the young and middle-aged subjects were not significantly different from one another. The same trend in significant differences was observed for standing on one leg on normal floor or on foam support with eyes open. Somewhat unexpectedly, we observed no significant age differences between sway parameters when standing on one leg with eyes closed. Presumably, this result emerged from our practice of clipping off the last 2 seconds of data from the analysis when a fall occurred, most often for the elderly subjects. The greater tendency to fall, however, was captured by stance duration with eyes closed, which was influenced by age. The stance duration mean values of the elderly subjects (8.93 seconds) were significantly different from the values of the middle-aged (13.39 seconds) and young subjects (18.51 seconds); the middle-aged subjects were significantly different from the young subjects. Eighty-six percent of the elderly subjects compared with 64% of the middle-aged and 21% of the young subjects fell prior to the maximum test duration of 20 seconds when tested on one leg with eyes closed.

Stance-Related Tasks (Tandem Walking)

We considered this group of tasks separately because the task is intermediate between stance and gait. Age-related differences were observed for walking eight tandem steps on normal support. As Figure 5 shows, changes in sway with age were very similar to those observed with the stance tasks. That is, mean sway amplitudes considered as angles or angular velocities increased with age. The elderly subjects had significantly greater amplitudes compared with the young and middle-aged subjects when walking eight tandem steps on a normal surface (Figure 5). No significant age-related differences were observed for walking eight tandem steps on foam support; that is, reducing the amount of sensory inputs did not heighten age-related differences. However, similar trends of increased sway were observed when this task was performed on the foam support for the elderly subjects compared with the middle-aged and young subjects (Figure 5). Sway measurements were different across ages for the two tasks of normal and foam-support surfaces except for the range of roll angle. As expected, sway was larger for tandem walking on the foam support surface (Table 2).

Gait Tasks

Walking under various conditions (head movements or eyes closed).—Task duration was significantly longer for the elderly and middle-aged subjects compared with the young subjects when walking five steps with head rotating and when walking five steps with head pitching (see Figure 6). When walking five steps with eyes closed, task duration was similar for all age groups. Roll and pitch angle as well as the range of pitch velocity was significantly different across all ages between the tasks of walking five steps under various conditions (Table 2).

Elderly and middle-aged subjects had significantly lower pitch angular sway compared with young subjects for the two tasks of walking five steps with eyes closed and with head pitching. Only middle-aged subjects had lower pitch angular sway compared with young subjects for walking five steps with head rotating. Elderly and middle-aged subjects did not differ from young subjects in their angle of roll sway values for any of these three tasks, except that when walking while pitching the head, roll sway was larger in the elderly subjects compared with the middle-aged subjects. For all three of these tasks, elderly and middle-aged subjects had significantly lower roll and pitch velocity values than young subjects. In addition, when walking five steps with eyes closed, middle-aged subjects had significantly lower roll and pitch angular velocity values than other subjects (Figure 6). For the task of walking with eyes closed, we noted a gender difference for the angle of roll sway, which was larger in elderly women.

Overall, the increase in duration we observed for gait tasks was accompanied by a decrease in sway velocity with age. However, decrease in sway velocity was not as progressive as the increase in duration because, particularly for pitch velocity, the middle-aged subjects had the smallest velocities (see Figure 6). Furthermore, a negative correlation between increased duration and decreased velocity can be assumed only if the amount of angular sway is constant across age groups. In fact, for the tasks shown in Figure 6, the range of pitch angle was least for the middle-aged subjects. Thus, for tasks of normal walking with various degrees of added difficulty, the middle-aged subjects showed both decreased ranges of pitch angle and angular velocity compared with the young and the elderly subjects, regardless of changes in the task duration with age.

Walking up stairs or over barriers.—Surprisingly, task duration was the only variable significantly influenced by age when walking up and down stairs (Figure 7). Elderly subjects had longer task duration values compared with middle-aged and young subjects. The ranges of angular sway did not change with age; however, a trend for decreased ranges of velocity was observed with age (Figure 7). Walking over a set of low barriers showed a significant increase in task duration and an increase in roll and pitch angular sway with age (Figure 7). Elderly subjects had longer task duration values and greater roll and pitch angle values than both middle-aged and young subjects. The duration was longer in the elderly women than in the elderly men. Roll and pitch velocity measures failed to show any changes with age.

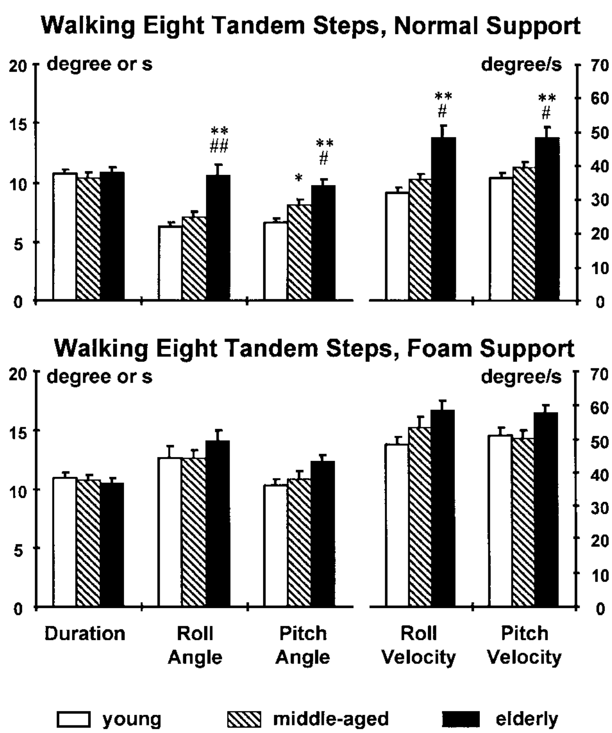

Figure 5. Sway means for the task of walking eight tandem steps on a normal and on a foam support surface. $*p < .05$ for elderly and middle-aged compared with young; $\#p < .05$ for elderly compared with middle-aged; $**p < .01$ for elderly and middle-aged compared with young; $\#\#p < .01$ for elderly compared with middle-aged.

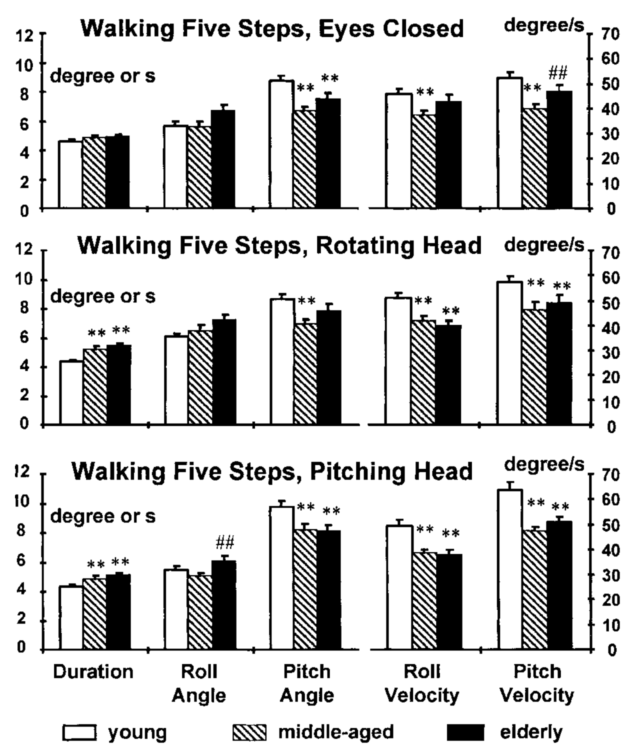

Figure 6. Decrease of population trunk angular sway means with age for gait tasks of walking five steps with either eyes closed, head rotating, or head pitching. Notice how task duration increases and sway decreases with respect to the young subjects with age. $*p < .05$ for elderly and middle-aged compared with young; $\#p < .05$ for elderly compared with middle-aged; $**p < .01$ for elderly and middle-aged compared with young; $\#\#p < .01$ for elderly compared with middle-aged.

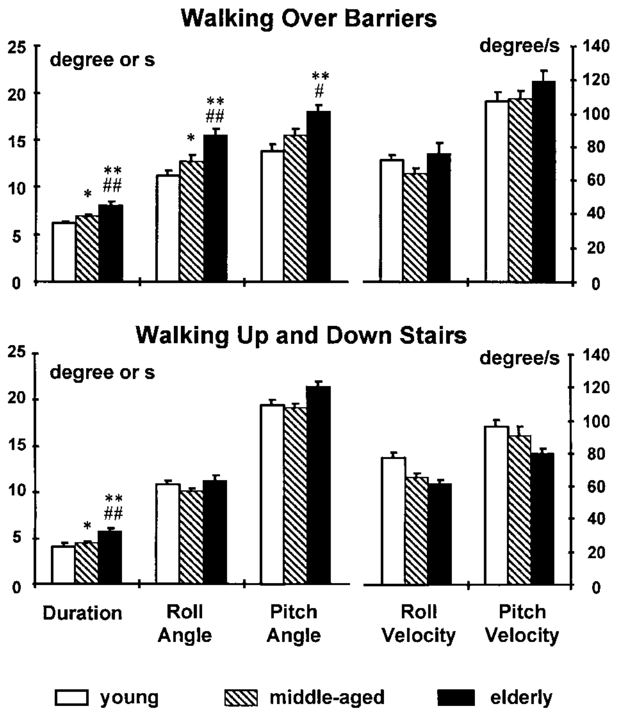

Figure 7. Changes in mean trunk angular sway with age for the tasks of walking over low barriers and walking up and down stairs. $*p < .05$ for elderly and middle-aged compared with young; $\#p < .05$ for elderly compared with middle-aged; $**p < .01$ for elderly and middle-aged compared with young; $\#\#p < .01$ for elderly compared with middle-aged.

Summarizing the results for gait tasks indicated that the relationship between a change in duration, range of sway amplitude, and sway velocity with age differed between tasks.

Discussion

Stance and Stance-Related Tasks: Influence of Age, Vision, and Proprioception

Stance tests showed several differences in balance control between the elderly group and the two younger age groups. There were few differences between the young and middle-aged groups; this concurs with other findings that, among normal subjects, deficits are not observed in balance performance before old age (15,23,24,25). The peak-to-peak ranges of trunk sway became greater when the different sensory systems were challenged. Eyes-closed conditions proved to be more difficult (greater sway was observed) than eyes open conditions, and a foam support surface was found to be more challenging than a normal support surface.

In our protocol, two-legged static posture was examined under four different conditions to evaluate the influence of the sensory systems on stance tasks. Absence of vision had detrimental effects on performance for all two-legged stance tasks. Trunk sway increased three-fold on eye closure (Figure 3); however, the statistical differences of elderly subjects were not remarkably higher than those of the younger subjects (Figure 3). These findings suggest that although the role of vision in balance control becomes increasingly more important with age, as several previous studies have also concluded (1–3), the integration of other, balance-related, sensory inputs is probably equally important. Vision is primarily used in controlling low frequency disturbances and, in conjunction with vestibular information, is essential for stabilizing upright posture in the case of a sudden or continuous disturbance (21,26,27). In elderly persons, the role of vision and vestibular inputs may be increasingly important compared with the young persons due to a decreased accuracy from lower-leg proprioceptive inputs (28–30) but also due to a general slowing of the conduction velocities of proprioceptive sensory signals (1). A similar trend of gradually declining performance with age was seen in trials requiring an altered use of lower-leg proprioception (foam support surface). The differences across ages were less significant on a foam support than those seen with eyes closed on a normal support, again suggesting that visual and vestibular inputs are more important than proprioceptive inputs in the control of quiet stance.

Afferent input from various mechanoreceptors and muscle spindles provides information about body position and movement. Lower-limb proprioception has been thought to be important in triggering early responses to perturbations (31); however, more recent findings suggest that ankle proprioception is not essential for triggering balance corrections (32). In our experiments, the foam support surface was used to provide a different use of somatosensory information from the lower leg for the task of standing compared with the use of somatosensory information from a firm surface. If proprioceptive information is to be considered the most important source of afferent information in balance control during stance (2,6,15), it would be expected that this condition would pose a greater challenge than eyes closed. Our results could not confirm the opinion that proprioception has a stronger influence than vision on stance control (6). It is clear from our results that eye closure provided a more challenging condition than a foam support because the eyes-closed tests resulted in the greatest ranges of peak-to-peak amplitude for angular displacements and velocities and highly significant age effects. The role of proprioception in stance has been examined in experiments with proprioceptive-deficient subjects and by implementing various techniques to alter proprioceptive input (2). It has been clearly demonstrated that the absence of proprioceptive information from the ankles influences stabilizing responses to postural perturbations less than the absence of vestibular or visual sensory inputs (21,32,33). It remains an open question whether stance trials under various sensory conditions can be used to identify those at risk of falling due to lower-leg proprioception loss.

Single-leg stance has been tested in several protocols, and it has been shown that duration and performance decline with increasing age and that single leg stance is a marker of poor balance control (10), probably because of a loss of muscle strength (34). According to Lichtenstein (35), single-leg stance is the most important variable in measuring sway because 20% to 40% of walking is performed on one foot. Thapa (11) suggested that one problem with using single-leg stance to evaluate balance control is that many elderly subjects are unable to perform single-leg stance due either to a lack of muscle strength or to fear of performing this test. It is an open question whether this inability may also be considered a marker of poor balance.

Concerning the effect of age, a similar question can be raised for the task of standing on one leg with eyes closed. The majority of the elderly subjects began to fall and were unable to maintain stance on one leg after 10 seconds Although the duration of one-legged stance was shorter in the elderly subjects, sway characteristics in the pitch and roll directions prior to the fall were not different from those of the younger subjects. Comparing the eyes-closed and eyes-open results pinpoints the dilemma of test selection. For the pure pass-fail criterion, setting the duration at 5 seconds for the middle-aged subjects and 10 seconds for the elderly subjects on the basis of the lower 5% limit when standing on one leg with eyes closed might well be reasonable. However, such hard limits give little quantitative information about body sway. In contrast, standing on one leg with eyes open provides a longer period of sway to analyze and therefore more quantitative information. In fact, the latter test provided the most significant information of all our tests.

Gait Tasks: Influence of Age, Vision, and Proprioception

Although many tests examine stability during static posture, most falls occur during gait while performing normal daily activities (3,19,36) under less than optimal sensory conditions, such as decreased lighting or unexpected environmental conditions (5,19,37). There is also evidence that elderly persons who fall are not capable of performing another task, such as talking, while walking (38).

Results of the gait tasks also revealed the varying levels of performance when additional sensory-based tasks were introduced. Walking with eyes closed or with head movement produced significant differences between the groups. Remarkably, the elderly subjects performed the task with less sway than the young subjects. It is well known that visual and vestibular inputs are important sensory elements of gait execution. Placing more emphasis on vestibular inputs by asking subjects to simultaneously move their heads or close their eyes was bound to make the task more difficult for the elderly subjects. How they coped with this task provides insights into aging processes.

For gait tasks, duration for the elderly subjects was significantly longer than for the young subjects, and the amplitudes and velocities of trunk sway were less. It is possible that elderly persons are more apprehensive and therefore move more slowly, which would reduce their sway (39). On the other hand, the effect we observed could be due to a reduced range of hip and pelvic joint motion and an inability to bend the trunk more forward, forcing a faster rotation about the stance foot and an inability to extend the trunk backward to counteract increased stride length. Whatever the cause, the reduced and slower motion suggests that gait in elderly persons may not be more unstable; rather, elderly and even the middle-aged persons have adapted their locomotion to accomodate a stiffer, aging body (40,41). It could be argued that we should have forced the elderly and middle-aged subjects to move at the same cadence as the young subjects. The idea of standardizing cadence was considered and rejected because we wanted to use our tests to predict probability of loss of balance during normal daily activities, and forcing subjects to walk with a faster cadence than natural would not reflect this. Furthermore, when other authors asked elderly subjects to walk at the same pace as younger subjects, a reduction in trunk pitch displacements was still found (41), suggesting that changes in task duration and trunk sway angles are independent aging processes.

The unexpected results observed in the various gait tasks that required subjects to walk five steps point to possible differences in the control of stance and gait tasks. The significant differences between the young and middle-aged groups suggest that changes in sway angles due to a stiffening of the trunk may affect performance earlier for gait than for stance tasks and that a change in balance control may not necessarily mean greater body sway. Rather, it may suggest an inability to allow greater sway during gait instead of an attempt to keep sway more within the base of support provided by the feet. The fact that elderly subjects have slightly higher sway values than middle-aged subjects may be a reflection of their increased sway due to sensory deficits as observed with two-legged stance.

Camicioli and colleagues (23) found that the most difficult tasks were unable to distinguish between young and elderly subjects. Our results with the stairs and barriers tasks support this observation. For these obstacle tasks it can be seen that, whereas peak-to-peak amplitudes of the measurements increased with task difficulty (the largest velocities and sway angles of all tests), significance between groups was not achieved, due presumably to the higher variability in the measurement with increased task difficulty.

Advantages of the Current Protocol

The use of both stance and gait tasks provides a more complete assessment of balance control. As gait tests are thought to be more predictive of falling than stance tests (11), our protocol is more clinically oriented than currently available equipment tests. The component tasks of the protocol, comprised of clinical tests that have already been proven useful qualitatively, are improved upon with the addition of quantified measures. Many evaluation techniques examine only anterior–posterior sway, although medial–lateral sway has been shown to be a better predictor of falling tendency (20). Our device measures movement in both planes without the use of a platform or cumbersome equipment. This feature makes it particularly useful for the clinician.

The results of this study show that trunk sway measurement is a useful tool for the clinician assessing balance control. The significant differences found between age groups show that measurement of trunk sway is sensitive enough to detect age-related changes in postural control. The use of varied sensory conditions can provide insight into the possible origin of a balance problem. The variety of the tasks included in the protocol allows for a thorough investigation of different types of activities or postures that could indicate postural instability. Additionally, the measurement device is simple enough that the complete assessment protocol requires only 10 to 15 minutes to conduct and can be administered by one person. To expand on the clinical use of this measurement tool, future studies will examine the balance strategies of specific patient populations to determine characteristic patterns associated with each group, and test-retest reliability will need to be investigated.

Acknowledgments

This study was supported by the Swiss National Science Foundation Grant 593199.99 as well as a grant from the Novartis Foundation and the Free Academic Society of Basel to J.H.J. Allum.

Address correspondence to Professor J.H.J. Allum, University HNO-Klinik, Petersgraben 4 CH-4031, Basel, Switzerland. E-mail: jallum@uhbs.ch

References

1. Perrin PP, Jeandel C, Perrin CA, Béné MC. Influence of visual control, conduction, and central integration on static and dynamic balance in healthy older adults. *Gerontology*. 1997;43:223–231.
2. Whipple R, Wolfson L, Derby C, Singh D, Tobin J. Altered sensory function in balance in older persons. *J Gerontol*. 1993;48(special issue):71–76.
3. Berg K. Balance and its measure in the elderly: a review. *Physiother Can*. 1989;41:240–246.
4. Kane RA, Kane RL. Assessing the elderly: a practical guide to mobility problems in elderly patients. *J Am Geriatr Soc*. 1986;34:119–126.
5. Patla A, Frank J, Winter D. Assessment of balance control in the elderly: major issues. *Physiother Can*. 1990;42:89–97.
6. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction on balance. *Phys Ther*. 1986;66:1548–1550.
7. Fugl-Meyer AR, Jaaski L, Legman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. *Scand J Rehabil Med*. 1975;7:13–31.
8. Jebsen RH, Trieschmann RB, Mikulic MA, Hartley RB, McMillan J, Snook ME. Measurement of time in standardized test of patient mobility. *Arch Phys Med Rehabil*. 1970;53:170–175.
9. Mikulic MA, Griffith ER, Jebsen RH. Clinical applications of a standardized mobility test. *Arch Phys Med Rehabil*. 1976;34:119–126.
10. Potvin AR, Syndulko K, Tizrtellotte WW, Lemmon JA, Potvin JH. Human neurologic function and the aging process. *J Am Geriatr Soc*. 1980;28:1–9.
11. Thapa PB, Gideon P, Fought RL, Kormicki M, Ray W. Comparison of clinical and biomechanical measures of balance and mobility in elderly nursing home residents. *J Am Gertiatr Soc*. 1994;42:493–500.
12. Tinetti ME. Performance-oriented assessment of mobility problems in elderly patients. *J Am Geriatr Soc*. 1986;34:119–126.
13. Gabell A, Simons MB. Balance coding. *Physiotherapy*. 1982;68:286–288.
14. Mathias S, Nayak USL, Isaacs B. Balance in elderly patients: the "get-up and go" test. *Arch Phys Med Rehabil*. 1986;67:387–389.
15. El-Kashlan HK, Shepard NT, Asher AM, Smith-Wheelock M, Telian SA. Evaluation of clinical measures of equilibrium. *Laryngoscope*. 1998;108:311–319.
16. Whitney SL, Poole JL, Cass SP. A review of balance instruments for older adults. *Am J Occup Ther*. 1998;52:666–671.
17. Horak FB. Clinical assessment of balance disorders. *Gait Posture.* 1997;6:76–84.
18. Cohen H, Blatchly CA, Gombash LL. A study of the clinical test of sensory interaction and balance. *Phys Ther*. 1993;73:346–354.
19. Quail GG. An approach to the assessment of falls in the elderly. *Aust Fam Physician*. 1994;23:873–882.
20. Maki BE, Holliday PJ, Topper AK. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. *J Gerontol Med Sci*. 1994;49:M72–M84.
21. Allum JHJ, Shepard NT. An overview of the clinical use of dynamic posturography in the differential diagnosis of balance disorders. *J Vestib Res*. 1999;9:223–252.
22. Nashner LM, Peters JF. Dynamic posturography in the diagnosis and management of dizziness and balance disorders. *Neurol Clin*. 1990;8:331–349.
23. Camicioli R, Panzer VP, Kaye J. Balance in healthy elderly: posturography and clinical assessment. *Arch Neurol*. 1997;54:976–981.
24. Shepard NT, Schultz A, Alexander NB, Gu MJ, Boismier T. Postural control in young and elderly adults when stance is challenged: clinical versus laboratory measurements. *Ann Otol Rhinol Laryngol*. 1993;102:508–517.
25. Chandler JM, Duncan PW, Studenski SA. Balance performance on the postural stress test: comparison of young adults, healthy elderly, and fallers. *Phys Ther*. 1990;70:410–415.
26. Carpenter MG, Allum JHJ, Honegger F. Vestibular influences on human postural control in combinations of roll and pitch planes. *Exp Brain Res.* 2001 (In press).
27. Teasdale N, Stelmach GE, Breunig A, Meeuwsen HJ. Age differences in visual sensory integration. *Exp Brain Res*. 1991;85:691–696.
28. Blaszczyk JW, Hansen PD, Lowe DL. Accuracy of passive ankle joint positioning during quiet stance in young and elderly subjects. *Gait Posture*. 1993;1:211–215.
29. Teasdale N, Stelmach GE, Breunig A. Postural sway characteristics of the elderly under normal and altered visual and support surface conditions. *J Gerontol Biol Sci*. 1991;46:B238–B244.
30. Ring C, Nayak US, Isaacs B. The effects of visual deprivation and proprioceptive change on postural sway in healthy adults. *J Am Geriatr Soc*. 1989;37:745–749.
31. Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. *Exp Brain Res*. 1990;82:167–177.
32. Allum JHJ, Bloem BR, Carpenter MG, Honegger F. Is lower-leg proprioception essential for triggering balance corrections? *Exp Brain Res*. 2000;130:375–391.
33. Allum JHJ, Honegger F. Interactions between vestibular and proprioceptive inputs triggering and modulating human balance-correcting responses differ across muscles. *Exp Brain Res*. 1998;121:478–494.
34. Hurley MV, Rees J, Newham DJ. Quadriceps function, proprioceptive acuity and functional performance in healthy young, middle-aged and elderly subjects. *Age Aging*. 1998;27:55–62.
35. Lichtenstein MJ, Shields SL, Shiavi RG, Burger MC. Comparison of biomechanics platform measures and videotaped measures of gait with a clinical mobility scale in elderly women. *J Gerontol Med Sci*. 1990;45:M49–M54.
36. Speechely M, Tinetti M. Assessment of risk and prevention of falls among elderly persons: role of the physiotherapist. *Physiother Can*. 1990;42:75–78.
37. Lipsitz LA, Jonsson PV, Kelly MM, Koestner JS. Causes and correlates of recurrent falls in ambulatory frail elderly. *J Gerontol Med Sci*. 1991;46:M114–M122.
38. Stelmach GE, Zelaznik HN, Lowe D. The influence of aging and attentional demands on recovery from postural instability. *Ageing*. 1990;2:155–161.
39. Tinetti ME, Richman D, Powell L. Falls efficacy as a measure of fear of falling. *J Gerontol Psych Sci*. 1990;45:P239–P243.
40. Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K. Stiffness control of balance in quiet standing. *J Neurophysiol*. 1998;80:1211–1221.
41. Kerrigan DC, Todd MK, Della Croce U, et al. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. *Arch Phys Med Rehabil*. 1998;79:317–322.

Received December 2, 1999
Accepted May 8, 2000
Decision Editor: John E. Morley, MB, BCh