Mobile Posturography: Posturographic Analysis of Daily-Life Mobility

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Objective: Mobility is crucial to maintain a sufficient quality of life. Posturography should be therefore focused on the investigation of daily-life activities ("mobile posturography"). Nowadays, postural control is often estimated by stance tasks on a force plate under different sensorimotor conditions. This technique applies an indirect approximation of the center of body mass and is not related to tasks required for mobility. An alternative approach would be the direct measurement of body sway during daily-life conditions close to the center of body mass. The present study was aimed at investigating normal age-dependent postural control strategies by analyzing the body sway of male and female subjects in daily-life tasks. Furthermore, the results were compared with data of age- and sex-matched vestibular disorders to determine the sensitivity of the "mobile posturography".

Study Design: Prospective study.

Patients: The patient group included 76 subjects, and the control group comprised a total of 246 healthy volunteers. Trunk sway measures were performed using the Vertiguard-D device.

Results: A nonlinear relationship between age and body sway was observed in majority of all the conditions. Furthermore, large sex-related differences in body sway were observed. The sensitivity of the mobile posturography was higher than determined during the SOT-force plate measurements or reported in literature before for state-of-the-art platform posturography.

Conclusion: The present results indicate that the method introduced here can quantify postural deficits in a broad range and in an inhomogenous sample of patients. Key Words: Body sway—Mobile posturography—Sensitivity.

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Mobility is crucial to maintain independence and quality of life. Diminished mobility leads to a significantly higher risk for morbidity, disability, and mortality (1). Posturography should therefore investigate daily-life activities to determine the mobility of an individual patient ("mobile posturography"). Nowadays, postural control is often estimated by stance tasks on a force plate under different sensorimotor conditions. This technique applies an indirect approximation of the center of body mass and is not related to tasks required for mobility. An alternative approach would be the direct measurement of body sway during daily-life conditions close to the center of body mass. Such measurements are currently easy to perform with commercially available measurement systems (e.g., Vertiguard). However, because of the increased degrees of freedom during more complex activities than standing, the individual results should be compared with well-matched age- and sex-related normative values. Age and sex could be crucial factors for the estimation of human postural control. Previous studies reported an age- and sex-related increase of the risk to fall (2). Falls that are the result of an age-related decline in sensorimotor and neuromuscular balance control are one of the major health concerns in adults (3). The postural control in humans, which is largely determined by sensory components (somatosensory, visual, and vestibular subsystem), the motor component, and an integrating control center (4) undergo a variety of structural and functional changes (5) during aging. This includes diminished muscle strength and volume, loss of muscle fibers, motor units (6), endplates, and synapses...
Furthermore, a deterioration of the peripheral vestibular sensors (8) was reported. Investigations of age-related differences in posture and movement control showed that the elderly tend to adopt cautious movement strategies that are typically defined by slower motor responses.

Compared with younger, elderly individuals exhibit slower walking velocity (9), increased obstacle-crossing time (10), and increased movement time during voluntary postural leaning (11). These slower responses may be used in an effort to facilitate dynamic postural stability (12) but may also simply reflect age-related degenerative changes in postural control (6,8).

The normal aging process is also consistently associated with an increased reaction time (13). Such increased postural rigidity during aging is often implicated in age-related alterations of coordination responses as the result of passive osseo-ligamentous changes of joints (14) or due to an active postural response strategy (15). However, this strategy depends largely on the specific sensorimotor condition.

Studies on age-related changes in postural control during stance tasks on force plate devices described a simple positive correlation of body sway with increasing age (16). Based on the observed age-related changes described previously, it seems to be very unlikely that there is such a simple correlation between age and body sway in complex daily-life conditions.

The present study was therefore aimed at investigating normal age-dependent changes of postural control by analyzing the body sway close to the center of body mass during dynamic and static daily-life conditions (mobile posturography). Furthermore, the results were compared with data of age- and sex-matched vestibular disorders to determine the sensitivity of the mobile posturography.

**MATERIALS AND METHODS**

The control group consists of 246 volunteers (137 female and 109 male subjects) without any history of ear, nose, and throat diseases nor of any vestibular disorder or of previous self-reported falls. The total sample (male and female) was divided into 7 age groups (20–89 yr). Each age group consisted of at least 15 participants.

The patient group included 76 subjects (27 female and 49 male subjects) aged between 33 and 78 years. All patients experienced a chronic noncompensated vestibular disorder or Parkinson disease (41 unilateral semicircular function loss, 10 acoustic neuroma, 10 Parkinson disease (Hoehn and Yahr stage IV), 8 presbyvertigo, and 7 unilateral otolith disorder).

Semicircular function was estimated using caloric irrigation (30°C/44°C). Acoustic neuroma was radiographic defined. For saccular and utricular testing, cervical vestibular evoked myogenic potentials and subjective visual vertical (SVV) during eccentric centrifugation (180 degrees per second) were investigated. Patients with presbyvertigo were older than 60 years and experienced vertigo. They showed normal results in all described diagnostic tests.

Trunk sway measures of postural stability were performed using the Vertiguard-D device (Vesticure GmbH, Pforzheim, Germany). This lightweight device (180 g) is battery driven and allows free movements of the subject, whereas 2 inbuilt gyroscopes (resolution 0.018315 degrees per second—14 Bit) record the angular velocity of the trunk with a sampling rate of 80 Hz in 2 dimensions. The Vertiguard-D was fixed by a belt at the hip (close to the center-of-body-mass) and connected to a computer (Fig. 1). For each measurement, the angular velocity in the roll and pitch planes were sampled and analyzed by the Vertiguard software using the median of all data points.

The measurement of angular sway velocity could be an advantage for the analysis of aggravating patients because they often show a slow high angle sway. However, one or more momentary wide-amplitude sway excursions during the measurement period also could influence the median strongly if they occur with a high velocity (possible sway pattern in patients with vestibular disorders).

To guarantee the reliability of all measurements, the device performed an automatic self calibration before each measurement and compensated a possible sensor drift (induced by, e.g., temperature changes) continuously.

During the measurements, the subjects had to undergo without shoes the standard balance deficit test (SBDT) (17). This test is based on the Tinetti’s test (18) and the Clinical Test of Sensory Interaction in Balance (19).

![FIG. 1. Schematic picture of the Vertiguard-D application for mobile posturography.](image-url)
All subjects older than 59 years performed the geriatric standard balance deficit test (gSBDT) where some difficult tasks were skipped (e.g., standing on one leg on foam), and the “Timed Up and Go test” (TUG according to (20)) was added.

The SBDT included the following tasks (in the performed order): standing on 2 legs with eyes open/closed, standing on 1 leg with eyes open/closed, 8 tandem steps (1 foot in front of the other) with eyes open, standing with 2 legs on a foam support surface (height 10 cm; density 25 kg/m3) with eyes open/closed, standing on 1 leg on a foam support surface, 8 tandem steps on a foam support surface, walking 3 m while rotating the head, walking 3 m while vertically pitching the head in rhythm, walking 3 m forward with eyes closed, walking up/down stairs (step height 23 cm), and walking over 4 barriers (height 26 cm with an interbarrier distance of 1 m).

The following tasks were skipped in the gSBDT: standing on 1 leg with eyes closed, standing on 1 leg on a foam support surface, and walking up/down stairs (step height 23 cm).

The modified TUG-test (stand up and sit down) was added as last conditions of the gSBDT.

The total testing time was between 6 and 10 minutes. Each subject performed each condition only once during the testing.

Specific Analysis of the Control Group

The median of results obtained from all group members was calculated to reflect the most characteristic feature of the trunk sway within a specific age and sex group (21). Extreme values were identified within each sex and age group by applying the Grubbs’ test (22). All extreme values (approximately 1% of all measurements) were excluded from the further analysis because the study was aimed at investigating central tendencies of human body movements during complex daily life conditions.

A piecewise linear regression was fitted on the course of the age-related body sway. For all parts of the piecewise regression (identified by a different slope), the correlation coefficient was calculated in pitch and roll direction.

The differences between male and female body sway were compared in all age groups by the t or U test (depending on data distribution). The distribution of the data was tested using the Kolmogorov-Smirnoff-Test. The level of significance was $p < 0.05$ for all statistical procedures.

Specific Analysis of the Patient Group

The median of body sway in roll and pitch direction was compared for each task with the age- and sex-related values obtained from the control group. The following formula was applied to calculate a composite score for the estimation of the total performance of a patient in relation to healthy controls:

$$\text{SBDT composite score} = \frac{\sum p\% + \sum r\%}{n \times 400}$$

with: $p =$ pitch sway / normal value in %, $r =$ roll sway / normal value in %, $n =$ number of tasks in the SBDT / gSBDT.

The SBDT composite score was further used to determine the sensitivity of the method. Patients with a composite score of 50 or higher were classified as pathologic. This is based on the result of the formula above for 100% age and gender-related sway—viz. if a patient shows the same sway during a condition as determined in age- and sex-related controls, his sway value for the calculation is 100 (100% of normative sway). If this holds true for all directions (roll and pitch) and conditions of the SBDT, the composite score is 50 (based on the calculation of the formula above).

Furthermore, each patient performed the sensory organization test (SOT) on the ankle sway referenced system (platform) BalanceMaster (Nicolet Biomedical, Clackamas, OR, U.S.A.). In contrast to the measurement of sway velocity close to the center of body-mass (e.g. Vertiguard-D), an ankle-sway referenced system (e.g., BalanceMaster) estimate center-of-body-mass movements by calculating the center-of-pressure within the plantar area. The SOT contains six sensorimotor standing conditions. The SOT composite score is scored between zero and 100 (maximal stability) and was used for further analysis. All patients were also asked to fill in the Dizziness Handicap Inventory (DHI) questionnaire.

Our Institutional Review Board approved the study protocol. The subjects gave their written, informed consent to participate in the study.

RESULTS

Male Subjects

The trunk sway increased with the increasing age in only 5 of 17 tasks (Fig. 2). This was especially true for tasks with enhanced requirements on the musculoskeletal strength or coordination. A clear linear relationship between trunk sway and age was observed in the pitch direction during walking up and down stairs ($R = 0.92$, $p = 0.02$). A strong positive correlation between trunk sway and age also exists during standing on one leg ($R = 0.92$, $p = 0.004$; pitch $R = 0.83$, $p = 0.02$) or standing on two legs on a foam support surface with closed eyes ($R = 0.77$, $p = 0.04$; pitch $R = 0.87$, $p = 0.02$). In some tasks (e.g. walking-eyes open/closed, walking 8 tandem steps on a foam support surface), an increase of trunk sway could be observed until a distinct age limit. Above this age, a decline in trunk sway was found with increasing age. The age at which the trunk sway decreased was largely dependent on the performed task (Fig. 2).

Figure 3 compares the effect of different sensory conditions on trunk sway during the similar motor task. The influence of the visual input on postural control in the roll direction is increased with aging. This holds particularly true for the two- and one-leg stance tasks (especially if the proprioceptive input was reduced) as well as for the gait tasks. A similar effect of a reduced visual input on trunk sway in the pitch direction was only recognizable in the one-leg stance tasks.

The influence of the proprioceptive input on postural control seems to be not affected in these stance tasks by age. During walking tasks, younger subjects (up to 60 years) decreased their trunk sway if the visual input was diminished or the vestibular receptor function was biased by head movements. Elderly male showed an increase of trunk sway in roll and a decrease in pitch direction under these conditions with increasing age (Fig. 3).

Female Subjects

In 9 of 17 tasks, the trunk sway increased with aging (Fig. 4). This was especially true for stance or walking tasks with high demands for the maintenance of postural control (e.g., tandem steps). A linear, positive correlation...
FIG. 2. Trunk sway median in pitch and roll direction of male subjects (aged between 20 and 89 yr) during different sensorimotor conditions. Dashed lines indicate a changed slope of the piecewise linear regression. The correlation coefficient ($R$) is given within all parts of the piecewise regression.

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between trunk sway and age was observed during standing on one leg with eyes closed (roll $R = 0.99$, $p = 0.003$; pitch $R = 0.83$, $p = 0.04$) and in pitch direction while performing 8 tandem steps on a normal surface ($R = 0.77$, $p = 0.04$) or on foam ($R = 0.92$, $p = 0.02$). In some tasks (e. g. stand up, sit down), an increase of trunk sway could be observed until a distinct age, followed by a decline of trunk sway with aging. The age at which the trunk sway was declined depends largely on the performed task (Fig. 4). A near linear and statistically significant reduction of trunk sway with aging was observed in all normal gait tasks (not in the tandem-step walking tasks).

Figure 5 compares the effect of different sensory conditions on trunk sway during similar motor tasks. The influence of the visual input on postural control in the roll direction of the stance tasks was increased with aging. Similar results were found for the 2- and 1-leg stance tasks, particularly after reducing the proprioceptive input.
FIG. 4. Trunk sway median in pitch and roll direction of female subjects (aged between 20 and 89 yr) during different sensorimotor conditions. Dashed lines indicate a changed slope of the piecewise linear regression. The correlation coefficient ($R$) is given within all parts of the piecewise regression.

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When the visual input was reduced, the same influence on trunk sway in the pitch direction could be demonstrated for the one-leg stance tasks. The proprioceptive impact for postural control was only increased by aging in the 1-leg stance tasks.

During walking tasks, the reduction of trunk sway decreased with aging if the visual input was diminished or the vestibular receptor function was biased by head movements. Female subjects older than 70 years showed a slight increase of trunk sway only in the roll direction under some of these walking conditions (Fig. 5).

**Sex-Related Differences in Postural Control**

Male subjects showed a significantly higher trunk sway under most of the stance conditions compared with female subjects. This holds especially true for age groups older than 40 years (Figs. 2 and 4).

There is a marked age-dependent relationship between male and female trunk sway during walking tasks. In female subjects, the trunk sway was markedly expressed compared with male subjects until the age of 40 years. Between 40 and 60 years of age, female subjects showed a reduction in sway during walking, whereas male subjects usually develop an extended trunk sway. Above this age limit, the male subjects reduce the extent of trunk sway and the gender-related differences in gait become definitely smaller (Figs. 2 and 4).

**Patients With Chronic Noncompensated Vestibular Disorder or Parkinson Disease**

Measurements could be easily performed in almost all patients. The SOT composite score showed a pathologic result in 63% of all patients with a balance disorder. Sixty-five percent of patients with reported falls were correctly classified by this method. The SBDT composite score reached a pathologic value in 82% of all investigated patients. Seventy-eight percent of all patients with reported falls showed in total a pathologic sway in the SBDT.

Not all patients with chronic noncompensated vestibular disorders had balance problems. This was reflected by the relative low DHI mean value (48.4) and a high standard deviation (23.7). The correlation between the SBDT composite score and the DHI is shown in Figure 6. There is a statistically significant relationship between both values (correlation coefficient, 0.7).

**DISCUSSION**

The present study describes the trunk sway as indicative of postural control under different, daily-life conditions over a whole life span. Our findings suggest that the assumption of a general increase in sway with aging is oversimplified. After careful analysis, specific tasks or conditions could be identified where the opposite holds true.

An increase in body sway with aging could only be observed under those conditions which require a highly developed musculoskeletal reactivity and/or coordinative action (e.g., walking on stairs in male subjects, standing on one leg in male and female subjects).

A nonlinear relationship between age and body sway was observed in majority of all the SBDT conditions. The absolute sway pattern could be best described as “hockey-stick” function, which is characterized by a maximum of sway at a special decade within the life span. Male subjects are characterized by this “hockey-stick pattern” in walking tasks in contrast to female subjects who have a near linear decrease in sway with aging. However, both sex groups decrease their trunk sway significantly during all walking tasks between 60 and 89 years of age.

This would suggest that the reduction of sway during walking is an adopted strategy to prevent falls. Although a rigid movement strategy can reduce the amplitude of sway excursion, this strategy may not always represent the most optimal method for achieving dynamic stability as the degrees of freedom available for the performance of voluntary movement and compensatory postural responses are reduced (23). This could be related to the fact that falls in older adults occur most commonly during walking or at least out of a movement pattern, not while standing (24).

The influence of age on gait and postural stability was investigated earlier also by other groups with different techniques. Schrager et al. (25) measured the body sway of subjects between 50 and 95 years with a set of 37 retroreflective markers, which were placed on bony landmarks of the arms, legs, trunk, and head. The calculated deviation and velocity of the center of mass increased with increasing age. However, this is not related to the trunk sway measure at the center of body mass as performed in the present study. The integration of sway data obtained from the arms, legs, trunk, and head reflects more the efforts to maintain the postural control than the body sway itself.

Hegemann et al. (21) used a mobile posturography system to investigate subjects aged 6 to 82 years. They reported that age and height contributed equally between 7 and 25 years to postural stability, whereas height did not more influence it more than 25 years of age. They also showed large variations in trunk sway during the whole life span. However, this study lacks a sex-specific analysis.

**Sex-Related Differences**

The large sex-related differences in body sway as depicted in the present study has not been found in the literature, and in this direction, we made a logical attempt to fill this lacuna, which is of paramount importance.

Male subjects seem to have a larger body sway under nearly all tested conditions, particularly in those subjects over 40 years of age. Female subjects are characterized by a greater trunk sway during most gait and stance tasks in the age groups below 40 years.

Previous studies used a similar methodology, but there is no sex-specific analysis of their data (26). A qualitative assessment of postural control only by TUG and Romberg’s test has been performed (27), or only very young adults were included in the study (28). Hence, our data are not comparable with these results.
In the present study, the effect of age on postural control was not sex specific in some of the tested conditions (e.g., obstacle crossing). The results of these conditions are in accordance with earlier studies. Hahn and Chou (29) also showed an increased sway in roll direction and a decreased sway in pitch direction as has been reported here during obstacle crossing of the elderly.

Influence of Visual and Proprioceptive Inputs
The importance of visual information for the postural control among elderly has already been described in previous investigations (5,6,21). Accordingly, the visual input becomes more important with aging as proprioceptive information might not be fully available for other medical conditions, for example, diabetes and microcirculatory disorders of the lower limb. (8). This is in line with our findings in both the sexes as described in test conditions of one-leg stance and the walking tasks. In contrast to this, the proprioceptive input had a greater impact on postural control than the visual one during the two-leg stance tasks (all age groups). Aging effects could only be demonstrated when both inputs (i.e., visual and proprioceptive) were

![Graphs showing differences in trunk sway between two age groups](image)

**FIG. 5.** Changes of the trunk sway median in pitch and roll direction during reduced or disturbed visual, somatosensory, or vestibular information. Measures were taken during 3 different motoric tasks from female subjects aged between 20 and 89 years.
of patients. Objective measurement of postural control (mobile posturography) is superior to the subjective DHI score. The correlation between the subjective DHI score and the composite score calculated from sway measures during the SBDT was not very high in our study group. However, the high DHI score calculated from sway measures during the SBDT might reflect the risk to fall in those elderly out of a movement pattern as described frequently (13,24).

Interestingly, a biased visual or vestibular input can diminish trunk sway during walking to a certain age limit. Thereafter, trunk sway is increased as an aging effect and might reflect the risk to fall in those elderly out of a movement pattern as described frequently (13,24).

The data obtained with a mobile posturography system enunciates that apart from aging, individual postural control depends on other multifocal aspects, namely, visual, proprioceptive, and vestibular inputs; on sex; and on the specific sensorimotor task or requirement of daily life. On one hand, aging as a physiologic process does not necessarily imply the risk to fall, if the elderly subject does not face other postural challenges. On the other hand, the postural deficits can be assessed individually by those body sway recordings as described previously.

The sensitivity of the mobile posturography shown here was higher than determined for the same patients with state-of-the-art platform posturography methods. The platform posturography results shown in the present study corresponds well with previous reported data (31).

The high sensitivity of the mobile posturography was especially surprising because the average DHI value was not very high in our study group. However, the high DHI standard deviation shows that some patients experienced dizziness, whereas others do not. Nevertheless, the correlation between the subjective DHI score and the objective measurement of postural control (mobile posturography) was significant and sufficient. This indicates that the method introduced here can quantify postural deficits in a broad range and in an inhomogenous sample of patients.

In essence, the results of the present study clearly show that the mobile posturography is a powerful tool for the individual analysis of postural deficits in daily life activity.

REFERENCES


