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Development and Evaluation of an Accelerometry System Based On Inverted Pendulum to Measure and Analyze Human Balance

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Abstract. An accelerometry system was developed based on the inverted pendulum model and its effectiveness to measure the body's sway path and sway angle was verified in healthy adult volunteers. Sway path represents the body's movement from its center of mass position projected to the ground surface while sway angle represents the body's orientation from the vertical. Mathematical models were developed to determine the sway displacement and sway angle from the accelerometry system. The resulting values were compared with the manual measurements obtained from a plumb bob based setup and found to correlate closely. Using the developed system, measures that analyzed the contribution of the visual, somatosensory and vestibular systems to balance were obtained. It was found that the accelerometry system followed the principle of motion of an inverted pendulum and provided information that can assist in better understanding of balance and thus it may assist clinicians in diagnosing balance dysfunctions.

Keywords: Accelerometry, Balance assessment, Sway path, Sway angle.

1 Introduction

The maintenance of balance in humans requires a combination of mechanisms involving the skeletal, neuromuscular and sensory systems. Balance is the ability to correctly maintain the body's center of mass over its base of support [1]. Balance dysfunctions are the primary cause of falls in the elderly. A decline in the functionality of the vestibular system, somatosensory system and visual system with age in the elderly has been reported [2-4]. This decline can in turn reduce the elderly's ability to maintain balance. The main factors contributing to postural instability in the elderly include muscle weakness, longer reaction time and reduced peripheral sensation. The fear of falling can restrict participation in general daily activities and falls are the leading cause of deaths in the elderly [5-7].

Balance disorders have different causes and can be grouped into vertiginous and non-vertiginous disorders [8,9]. Vertiginous disorders (vertigo) are a rotating or spinning motion associated with problems with the vestibular system. Non-vertiginous disorders such as light-headedness, motion intolerance, imbalance, floating, unsteadiness and tilting sensations are associated with cardiovascular diseases, e.g. those found in Parkinson disease [8,9]. Timely diagnosis of balance problems can reduce associated falls [10,11].

Balance examinations can be performed in static and dynamic scenarios using a number of subjective approaches. These approaches have varying complexity, reliability and validity [11]. They include the Berg Balance Scale, the Modified Clinical Test of Sensory Interaction on Balance (M-CTSIB), the Functional Reach Test, the Tinetti Balance Test of the Performance-Oriented Assessment of Mobility Problems, the Timed "Up and Go" Test, and the Physical Performance Test (PPT). Some of these tests are used in balance examination in dynamic conditions (i.e. Berg Scale, Tinetti and Physical Performance Test) while others are suitable for static conditions (i.e. M-CTSIB and Functional Reach Test) [11].

Balance examinations can be based on posturography equipment. Clinically acceptable equipment for posturography should be portable, cost effective, accurate, reliable and easy to use [11]. Force platforms can be used for posturography. They measure the center of foot pressure (COP) displacement in a quiet stance (standing still) position. Force platforms are costly and available only in specialized centers. With the advancement in electronics, miniaturized electronic devices capable of measuring motion have been developed. These devices that are also known as Inertial Measurement Unit (IMUs) are cost effective, can be worn and provide detailed information about the body’s movement. An IMU typically contains an accelerometer that measures directional acceleration (forward/backward) and a gyroscope that indicates the rate of rotation. For the past decades the use of IMUs for measuring human balance has been reported. These provide evidence of the validity of these devices in motion measurements and for balance problem examinations [12,13].

In this paper accelerometry refers to the technique of using an IMU to measure body movement. Accelerometers were used to evaluate static and dynamic balance functions in children [14]. The use of an inertial sensor to quantitatively describe postural control strategy during lying-to-sit-to-stand-to walk tasks has been reported [15]. The majority of these systems only measure dynamic stability. The measurement of standing balance has been reported to play an important role in balance assessment [16]. Standing balance has been evaluated to be useful in the Modified Clinical Test of Sensory Interaction on Balance (M-CTSIB) [16].

In the following sections, the M-CTSIB test used in this study is explained and an accelerometry approach to measure the body's displacement and orientation in sway analysis is described. Its accuracy is evaluated using a developed setup similar to that of an inverted pendulum to determine sway displacements and orientation angles.

2 Accelerometry Technique for Measuring Balance

In the analysis of human balance several authors have provided evidence that body sway during quiet standing can be compared to the motion of an inverted pendulum [17-19]. An inverted pendulum is a pendulum that has its center of mass above its pivot point [19].

In accelerometry based body sway analysis, the signals from an inertial measurement unit (accelerometer or gyroscope) that is placed on the body's center of mass (COM) position are processed to determine body's movements and orientation angles during a quiet standing position. This sway analysis can provide valuable information such as sway path plot and sway polar plot. A model for evaluating standstill balance is shown in Figure 1 and described by equations 1 and 2, where A is the resultant acceleration, $\cos\alpha, \cos\beta$ and $\cos\gamma$ are directional cosines of the accelerations a_x, a_y, and a_z in the x, y and z axes of the accelerometer, D is the combined coordinate distance, d_z is the position of the sensor from the ground representing the center of mass position of a body. In this paper centimeters (cm) and centimeters per second square (cm/s^2) are used for displacements and accelerations respectively.

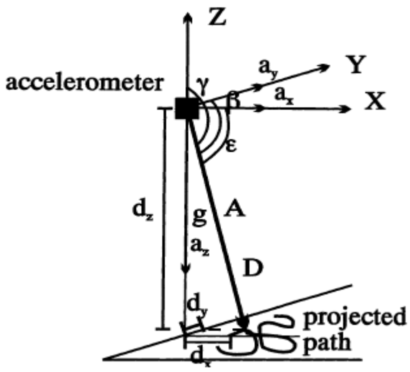


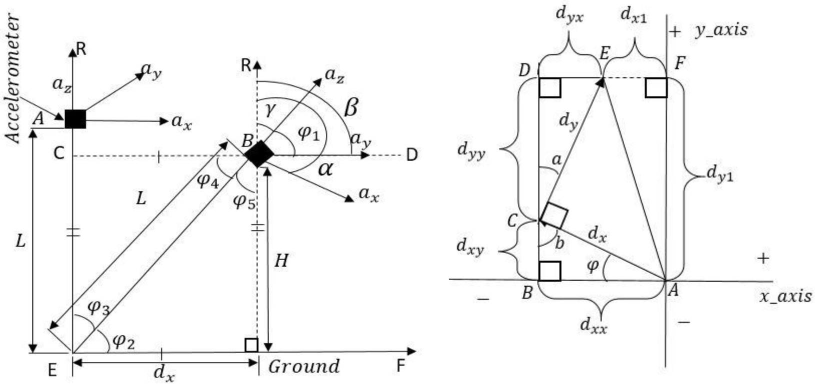
Fig. 1. Obtaining the displacement of the tri-axial accelerometer on the ground surface (Source: Mayagoitia et al, (2002)).

$$A = \sqrt{a_x^2 + a_y^2 + a_z^2}, \cos\alpha = \frac{a_x}{A}, \cos\beta = \frac{a_y}{A} \ and \ \cos\gamma = \frac{a_z}{A} \quad (1)$$

$$D = -\frac{d_z}{cos\gamma}, d_x = D\cos\alpha, d_y = D\cos\beta \quad (2)$$

Using this model, the projected displacements from the COM position to the ground, d_x and d_y, in the x and y directions can be obtained. The equations of the model are only valid provided the angle swept by the pendulum is small [20]. The limitation of this model relates to not fully conforming to the motion of an inverted pendulum.

In this study, a model for analyzing human balance is introduced as shown in Figure 2. This model uses a tri-axial accelerometer and a gyroscope to model an inverted pendulum system.



(a) (b)

Fig. 2. Tracing of the sway displacement on the ground: (a) tri-axial accelerometer and (b) gyroscope using an inverted pendulum setup. R is the resultant acceleration in cm/s^2. L is the length of the rod in cm. H is the height above the ground surface in cm. a_x, a_y and a_z are accelerations in cm/s^2 in the x, y and z axes. α, β ,γ, a and b are angles in degrees. dx_1 and dy_1 are the resultant displacements in the x and y axes due to the rotational angle φ in degrees. d_{xx}, $d_{xy,}$ d_{yy}, and $d_{yx,}$ are coordinate displacements of the x and y axes of $d_{x,}$ and $d_{y,}$ respectively. $d_{x,}$ and d_y are ground displacements of the accelerometer.

The resultant acceleration (*R)* is the same as the resultant acceleration (*A*) obtained in [20] with directional cosines obtained from equation 1. The following equations can be established for the inclined accelerometer position (labelled as B) as shown in Figure 2(a).

$$\varphi_1 = 90 - \gamma, \gamma = \alpha - 90, \varphi_1 = 180 - \alpha \quad (3)$$

Line *CD* is parallel to *EF* (mathematical notation: $\overline{CD}$ // $\overline{EF}$) and Line $\overline{CE}$ // $\overline{DF}$ thus, $\varphi_2 = \varphi_1, \varphi_3 = \gamma$ (corresponding angles) and $\varphi_4 = \varphi_2$, $\varphi_5 = \varphi_3$ (alternate angles). Replacing all angles in Figure 2(a) by their corresponding and alternate angles, the sway displacement in the *x* axis and the height of the sensor from ground (*H*) are obtained. Using same operation, the sway displacement in the *y* axis is computed. These are given as:

$$d_x = -L\cos\alpha,\ d_y = -L\ \cos\beta,\ H = L\,cos\ \gamma \quad (4)$$

In Figure 2(b), the resultant displacements on ground $d_{x1,}$ and $d_{y1,}$ from the gyroscope in the *x* and *y* directions can be obtained from equations 5-8, where *a* and *b* are angles defined by the equations. All displacements and angles are in units of cm and degrees respectively. By resolving the angles and displacements, the resultant projected displacements (dx_1 and dy_1) on ground can be obtained using equations 7 and 8 respectively.

$$\hat{b} = 90 - \hat{\varphi}\,, \hat{\varphi} = 90 - \hat{b}\ ,\ \hat{a} = 90 - \hat{b}, \hat{a}=\hat{\varphi} \quad (5)$$

$$d_{xx} = d_x cos\varphi\ \ , d_{yy} = d_y cos\varphi, d_{yx} = d_y sin\varphi, d_{xy} = d_x sin\varphi \quad (6)$$

$$dx_1 = \ d_{xx} - d_{yx} = \ d_x cos\varphi - \ d_y sin\varphi \quad (7)$$

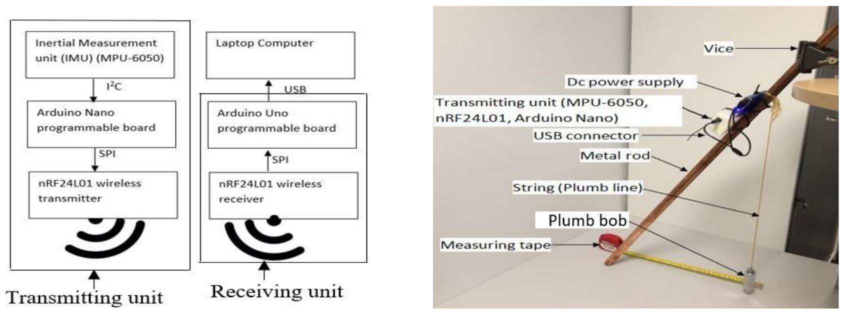
$$dy_1 = \ d_{yy} + d_{xy} = \ d_y cos\varphi + \ d_x sin\varphi \quad (8)$$

A gyroscope can be used in both cases of Figure 2 as a replacement of the accelerometer.

3 Evaluation Method of the Mathematical Models

3.1 Accelerometry System Evaluation

To evaluate the operation of the models an accelerometry system was developed. The system consisted of electronic subunits namely an inertial measurement unit (MPU 6050) with an integrated accelerometer and gyroscope, microcontroller boards (Arduino Nano and Uno board), a wireless transmitter and receiver module. The system has two main sections: the transmitter and receiver as shown in Figure 3(a). The setup used for evaluation consisted of a metal rod, a plumb bob connected to the end of a string which was attached at 100 cm height of the metal rod, and corresponding to the point where the accelerometry transmitting unit was connected as shown in Figure 3(b). The receiving unit of the accelerometry system was connected to a laptop computer using a USB connector. To evaluate the models, the rod was moved to varying angles at steps of 5 degrees from 0 to 45 degrees and its sway measurements (i.e. displacement and angles) were compared with the manual measurements obtained using the plumb bob setup as shown in Figure 3(b). The data of the accelerometer and gyroscope were recorded for 30 seconds at a sampling rate of 60 Hz. Data recording was carried out using Processing© software package and stored in the hard-disk drive of the laptop computer. A measuring tape was used to measure the displacements of the plumb bob on the ground and a protractor was used to measure the orientation angles of the rod. The orientation angle in this study is angle γ in degrees from equation 1.



(a) (b)

Fig. 3. Accelerometry system: (a) transmitting and receiving unit (b) and setup for evaluation

3.2 Balance Evaluation on Human Subjects

Balance evaluation was carried out on 15 healthy volunteers (nine males, six females; mean age and standard deviation: 22.5 and 3.4 years; age range: 18 to 31 years; mean weight and standard deviation: 70.9 and 7.5 kg; weight range: 56.2 to 79.7 kg; mean height and standard deviation: 173.5 and 9.8 cm; height range: 150 to 187.5 cm) with the accelerometry unit placed approximately on the COM position of the subjects. The COM position was just above the hip on the subject's back.

The four conditions defined by the Modified Clinical Test of Sensory Interaction on Balance (M-CTSIB) were used. These are defined as:

- Condition 1: Standing on a firm ground surface with eyes open.
- Condition 2: As in condition 1 but with the eyes closed.
- Condition 3: Standing on a flexible surface (sponge, thickness 8 cm) with eyes open.
- Condition 4: As in condition 3 but with eyes closed.

The data recording lasted for 30 seconds for each test condition. Similar processes of storing the data discussed in section 3.1 were used. Ethical clearance was received from the University prior to recording. The subjects declared to be physically fit and not to have ingested any substance that may affect their balance 48 hours prior to data recording.

3.3 Data Analysis

The data analysis was carried out using MATLAB© and SPSS© packages. The signals from the accelerometer and gyroscope were sampled at 60 Hz and combined using the complimentary filter algorithm shown in equation 9 for better performance to obtain the roll and pitch angle of the IMU device. θ_c and θ_{c-1} represents the current and previous roll or pitch angle, θ_g is the angular rate of the gyroscope in degrees per seconds, dt is the sample interval (time between successive samples) in second, a is the filter parameter and φ is the angle obtained from the accelerometer (α or β) in the x and y axes respectively. The filter parameter (a) was set to 0.8. The obtained angles were inputted into the displacements formulae of equations 2 and 4, to obtain the displacements on ground. The displacements ($D_{ML\,n}$ and $D_{AP\,n}$), velocities ($V_{ML\,n}$ and $V_{AP\,n}$) and accelerations ($A_{ML\,n}$ and $A_{AP\,n}$) on ground in Medio-Lateral (ML) and Anterior-Posterior (AP) directions were obtained using equations 10 and 11, where $D_{ML\,1}$ and $D_{AP\,1}$ are the first terms of the displacements in ML and AP directions and the nth and nth-1 terms are current and previous values, and T is the sampling period. The subtraction of the first term of the displacements was used to remove the offsets due to orientation problems of the sensor on the subjects back. Sway measures used to assess balance such as average displacements, velocities and accelerations in the ML and AP directions were computed using equations 12-14. The average displacements ($D_{ML\,av}$ and $D_{AP\,av}$), velocities ($V_{ML\,av}$ and $V_{AP\,av}$) and accelerations ($A_{ML\,av}$ and $A_{AP\,av}$) were measures of the mean of the absolute displacements, velocities and accelerations of the movement of the COM position from the origin, where N is the total number of samples. The range was defined as the difference between the maximum and minimum of each sway measure as shown in equation 15. All displacements, velocities and accelerations were in units of cm, cm/s and cm/s^2 respectively.

$$\theta_c = a \times \left(\theta_{c-1} + \theta_g \times dt\right) + (1-a) \times \varphi \tag{9}$$

$$D_{ML\,n} = D_{ML\,n} - D_{ML\,1}\,, D_{AP\,n} = D_{AP\,n} - D_{AP\,1}, V_{ML\,n} = \frac{D_{ML\,n} - D_{ML\,n-1}}{T} \tag{10}$$

$$V_{AP\,n} = \frac{D_{AP\,n} - D_{AP\,n-1}}{T}\,, A_{ML\,n} = \frac{V_{ML\,n} - V_{ML\,n-1}}{T}\,, A_{AP\,n} = \frac{V_{AP\,n} - V_{AP\,n-1}}{T} \tag{11}$$

$$D_{ML\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|D_{ML\,n}\right|\,, D_{AP\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|D_{AP\,n}\right| \tag{12}$$

$$V_{ML\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|V_{ML\,n}\right|\,, V_{AP\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|V_{AP\,n}\right| \tag{13}$$

$$A_{ML\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|A_{ML\,n}\right|\,, A_{AP\,av} = \frac{1}{N}\sum_{n=1}^{N}\left|A_{AP\,n}\right| \tag{14}$$

$$Range = |maximum - minimum| \tag{15}$$

Statistical tests were used to compare the displacements and angles of the methods A, B and C, and to compare the results from the sway measures of each condition of the M-CTSIB tests. Test of normality was carried out on the differences between each method and differences between each sway measure for each condition of the M-CTSIB test using the Shapiro-Wilk test. Statistical tests used for the analysis of the significant differences between the methods and between sway measures were based on the results of normality. If the differences were normal, a paired sample t-test was used otherwise Wilcoxon signed rank test was used to determine if a significant difference existed. The confidence level was 95%

The root mean square (RMS) values of the displacements ($D_{ML\,RMS}$ and $D_{AP\,RMS}$), velocities ($V_{ML\,RMS}$ and $V_{AP\,RMS}$) and accelerations ($A_{ML\,RMS}$ and $A_{AP\,RMS}$) are the square root of the means of the squared displacements, velocities, and accelerations. The RMS values of these measures in ML and AP directions are obtained using equations 16 through 18, where N is the total number of samples.

$$D_{ML\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(D_{ML\,n}\right)^2}\,, D_{AP\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(D_{AP\,n})^2} \tag{16}$$

$$V_{ML\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(V_{ML\,n})^2}\,, V_{AP\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(V_{AP\,n})^2} \tag{17}$$

$$A_{ML\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(A_{ML\,n})^2}\,, A_{AP\,RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(A_{AP\,n})^2} \tag{18}$$

4 Results and Discussion

This section explains the analysis and statistical test results. The statistical tests were based on paired sample t-test (when the differences between the variables were from a normal distribution) and the Wilcoxon signed rank test (when the differences between the variables were not from a normal distribution). The confidence level was 95%. The distributions of the differences were tested using Shapiro-Wilk test.

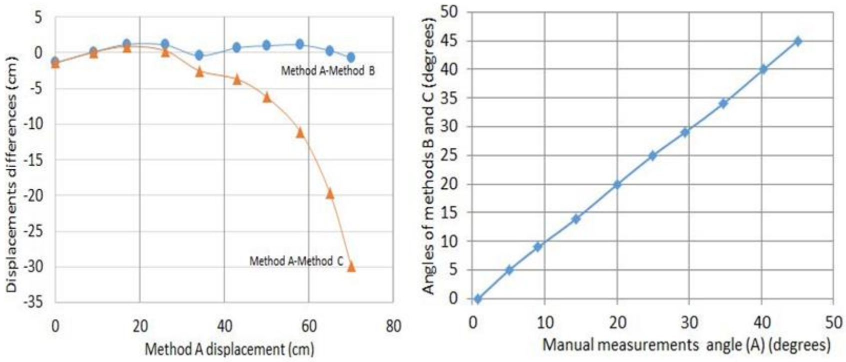
4.1 Results associated with the plumb bob based system

The displacement and angle values for methods A, B and C are shown in Table 1.

Table 1. Displacement and angle values in the y coordinate axis projected to the ground surface (x=0) for methods A, B and C.

Test number	Method A		Angles (γ) determined using methods B and C (degrees)	Method B	Method C
	Angle (degrees)	Displacement (cm)		Displacement (cm)	Displacement (cm)
1	0	0	0.8	1.4	1.4
2	5	9	5.1	8.9	8.9
3	9	17	9.1	15.8	16.1
4	14	26	14.4	24.9	25.7
5	20	34	20.1	34.4	36.5
6	25	43	25.0	42.3	46.7
7	29	50	29.4	49.0	56.2
8	34	58	34.7	56.9	69.1
9	40	65	40.3	64.7	84.7
10	45	70	45.0	70.7	99.9

Methods A, B and C represent the manual measurement (i.e. the plumb bob setup), the model developed in this study and the model reported in [20] respectively. Method A was used as the reference for the displacement and orientation angle for the other two methods. As seen from Table 1, the displacement values for methods A and B are close. The displacement values for method C deviates largely from those obtained from method A at angles larger than 20 degrees. The plots of the differences in displacements and angles between the methods B and C, and the reference (method A) are shown in Figure 4. The differences between the displacements for methods A and C, tested using Wilcoxon signed rank test, was statistically significant (p<0.05) while for methods A and B, the displacement differences tested using paired sample t-test were not statistically significant (p>0.05).

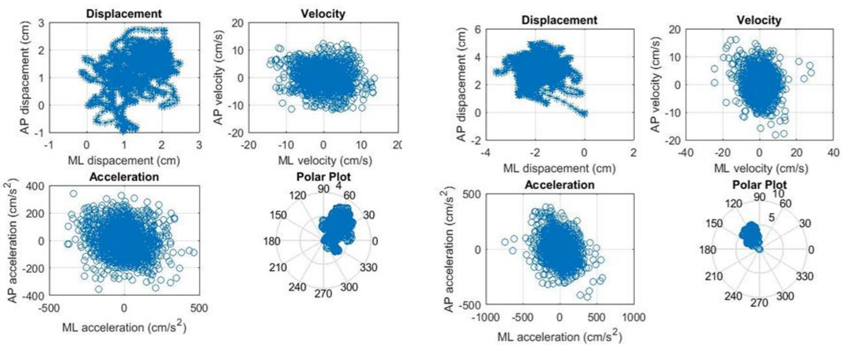


(a) (b)

Fig. 4. (a) Displacement differences between the methods and (b) orientation angles

4.2 Results associated with the human subjects

Examples of sway plots produced by the systems for one of the subjects in conditions 1 and 2 of the M-CTSIB test are shown in Figure 5.



(a) (b)

Fig. 5. Examples of displacement, velocity, acceleration and polar plots of a subject from M-CTSIB Test. (a) conditions: 1, (b) condition 2.

Sway measures used for analyzing conditions 1 to 4 are shown in Table 2. A tick mark indicates significant differences between the sway measures of the compared conditions using either the paired sample t-test or the Wilcoxon signed rank test, depending whether the differences in the measures being tested were from a normal distribution. The sway measures that provided highest differentiation between the four test conditions were selected from Table 2. The means and standard deviations of the associated measures are provided in Table 3. It was observed that none of the sway measures differentiated between conditions 2 (eyes closed standing on a firm surface) and 3 (eyes open standing on a flexible surface). Among these sway measures, range, average and RMS values of the velocities in the AP direction, and the average and RMS values of the accelerations in the AP direction provided largest differentiations amongst the four test conditions.

Table 2. Sway measures for the conditions 1 to 4. A tick mark indicates significant differences between the measures of the conditions. Distances, velocities and accelerations are in units of cm, cm/s and cm/s^2.

measures	M-CTSIB conditions					
	1 and 2	1 and 3	1 and 4	2 and 3	2 and 4	3 and 4
RMS distance-ML						
RMS distance-AP	✓				✓	✓
RMS velocity-ML						✓
RMS velocity-AP	✓	✓	✓		✓	✓
RMS acceleration-ML						
RMS acceleration-AP	✓	✓	✓		✓	✓
Range of distance-ML		✓	✓		✓	
Range of distance-AP		✓	✓		✓	✓
Range of velocity-ML						
Range of velocity-AP	✓	✓	✓		✓	✓
Range of acceleration-ML						
Range of acceleration-AP		✓	✓		✓	✓
Average distance-ML						
Average distance-AP						
Average velocity-ML						
Average velocity-AP	✓	✓	✓		✓	✓
Average acceleration-ML						
Average acceleration-AP	✓	✓	✓		✓	✓

Table 3. Means and standard deviations in bracket of the sway measures for the four conditions of M-CTSIB. Velocity in units of cm/s and acceleration in units of cm/s^2. 1: Eyes open standing on a firm surface, 2: eyes closed standing on a firm surface, 3: eyes open standing on a flexible surface and 4: eyes closed standing on a flexible surface.

measures	M-CTSIB conditions			
	1	2	3	4
RMS velocity-AP	2.3 (0.6)	2.7 (0.8)	2.8 (1.0)	3.6 (1.3)
RMS acceleration-AP	58.6 (15.0)	65.6 (18.8)	69.6(26.9)	85.9 (31.3)
Range of velocity -AP	16.3 (3.5)	23.5 (12.2)	24.1 (11.0)	33.7 (18.0)
Average velocity-AP	1.9 (0.5)	2.2 (0.6)	2.2 (0.8)	2.9 (1.0)
Average acceleration-AP	47.7 (12.8)	53.5 (15.1)	56.8 (21.0)	70.3 (25.2)

5. Conclusion

A system consisting of an inertia measurement unit (accelerometer and gyroscope) and wireless transmitter/receiver was developed. A body sway measurement algorithm based on the inverted pendulum model was devised that could accurately project the body's movement to the ground surface and determine its orientation angle related to the vertical. The system was used on 15 healthy adult volunteers to evaluate its effectiveness for analyzing the contribution of sensory inputs to human balance using a standstill balance test called the Modified Clinical Test for Sensory Interaction on Balance (M-CTSIB). M-CTSIB indicates the contributions of three sensory systems (i.e. visual, somatosensory and vestibular) to balance. The tests involve four measurement scenarios: eyes open and closed standing on a firm surface (conditions 1 and 2 respectively) and eyes open and closed standing on a flexible surface (conditions 3 and 4 respectively). Significant differences existed between conditions 1 and 2, 1 and 3, 1 and 4, 2 and 4, and 3 and 4 while no significant difference existed between conditions 2 and 3. The study indicated that accelerometry can provide valuable information that may assist with diagnosing balance dysfunctions.

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