Research Report – Research Article

Assessment of Postural Sway in Individuals with Multiple Sclerosis Using a Novel Wearable Inertial Sensor

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Keywords

Multiple sclerosis · Postural sway · Inertial sensors

Abstract

Balance impairment is common in individuals with multiple sclerosis (MS). However, objective assessment of balance usually requires clinical expertise and/or the use of expensive and obtrusive measuring equipment. These barriers to the objective assessment of balance may be overcome with the development of a lightweight inertial sensor system. In this study, we examined the concurrent validity of a novel wireless, skin-mounted inertial sensor system (BioStamp[®], MC10 Inc.) to measure postural sway in individuals with MS by comparing measurement agreement between this novel sensor and gold standard measurement tools (force plate and externally validated inertial sensor). A total of 39 individuals with MS and 15 healthy controls participated in the study. Participants with MS were divided into groups based on the amount of impairment (MS_{Mild}: EDSS 2–4, $n = 19$; MS_{Severe}: EDSS ≥ 6 , $n = 20$). The balance assessment consisted of two 30-s quiet standing trials in each of three conditions: eyes open/firm surface, eyes closed/firm surface, and eyes open/foam surface. For each trial, postural sway was recorded with a force plate (Bertec) and simultaneously using two accelerometers (BioStamp and Xsens) mounted on the participant's posterior trunk at L5. Sway metrics (sway area, sway path length, root mean square amplitude, mean velocity, JERK, and total power) were derived to compare the measurement agreement among the measurement devices. Excellent agreement (intraclass correlation coefficients >0.9) between sway metrics derived from the BioStamp and the MTx sensors were observed across all conditions and groups.

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Good to excellent correlations ($r > 0.7$) between devices were observed in all sway metrics and conditions. Additionally, the acceleration sway metrics were nearly as effective as the force plate sway metrics in differentiating individuals with poor balance from healthy controls. Overall, the BioStamp sensor is a valid and objective measurement tool for postural sway assessment. This novel, lightweight and portable sensor may offer unique advantages in tracking patient's postural performance.

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Introduction

Multiple sclerosis (MS) is a common neurodegenerative disease that affects a wide range of neurocognitive and physiological functions, including cognition, vision, sensation, coordination, and balance [1]. Impaired balance is a particularly debilitating symptom of MS, affecting an estimated 75% of patients during the progression of the disease [2]. Balance deficits in individuals with MS result from a myriad of factors, including slowed somatosensory conduction and impaired central integration [1]. Degradation in balance increases the risk of falls [3] and is often a focus of rehabilitation strategies [4, 5]. Therefore, objective balance assessment could be viewed as a critical biomarker for disease tracking and therapeutic intervention.

Traditionally, balance has been measured with rating scales [6] in clinical settings and force platforms [7] in research settings. Although widely used, clinical rating scales, such as the Berg Balance Test, often lack precision and depend on the clinician's expertise in administration and interpretation [8]. By contrast, force platform-based postural sway assessments have been demonstrated as valid and reliable measures of balance in health and disease [7, 9, 10] and are considered a gold standard. However, force platforms are relatively expensive, immobile and may not be practical for clinical and home-based assessments.

Recent improvements in inertial measurement technologies offer reliable and portable alternatives to the force plate-based postural assessment. Given that the goal of postural control is to maintain the center of mass (COM) within the limits of stability, direct measurement of COM may provide better insights into the mechanisms of balance control [11]. Numerous studies have reported using acceleration-based and gyroscope-based sway metrics for assessing balance deficits in older adults at risk of falling [12], in patients with Parkinson disease [13], MS [14, 15], and Alzheimer disease [16]. However, conventional inertial sensor(s) often still need to be synced with a host computer through additional hardware, and the sensor needs to be secured using straps or other means.

Recently, a wireless, skin-mounted inertial sensor, called BioStamp® (MC10 Inc., Lexington, MA, USA) has addressed these limitations with a body-conforming soft, flexible design that adheres directly to the skin with minimal preparation (Fig. 1). This novel sensor integrates a triaxial accelerometer and gyroscope with onboard flash memory and Bluetooth connectivity for clinical and home-based balance assessments. It can be synced and controlled with a tablet computer without any additional hardware, thus allowing a quick setup and portable recording of human movement. Recently, the validity of this system to measure gait in individuals with MS across the disability spectrum was reported [17].

Yet there is no information concerning the validity of the system to measure standing postural control. In this study, we characterize: (1) the concurrent validity of the BioStamp sensor in balance assessment compared to a reference accelerometer (MTx, Xsens Technologies B.V.); (2) the concurrent validity of this sensor in balance assessment compared to a force plate; and (3) whether acceleration measurement can reveal group differences in balance performance between healthy controls and individuals with MS in consistency with the force plate measurement.

Fig. 1. Example contents of a BioStamp wearable sensor system, and the illustration of sensor placement.

Methods

Participants

A total of 39 individuals with MS and 15 healthy controls (age-matched ± 2 years) participated in this investigation. Participants were recruited from previous participant pools and the local community. The inclusion criteria for MS participants involved a previously neurologist-confirmed diagnosis of MS, being able to stand upright for 30 s without aid and to walk for 6 min (with or without aid), and with either mild or severe self-reported disability. Self-reported disability was assessed with the self-reported Expanded Disability Status Scale (EDSS_{SR}), with a higher score indicating higher functional impairment. MS participants were divided into two groups based on the EDSS_{SR} [18] (mild: EDSS 2–4, MS_{Mild}; severe: EDSS ≥ 6 , MS_{Severe}). Inclusion criteria for healthy controls required no history of neurological or orthopedic conditions that might influence balance or mobility, and the ability to stand upright for 30 s without aid and to walk for 6 min (with or without aid).

Procedure

Upon arrival at the research laboratory, participants were verbally informed of the experimental procedures and provided an opportunity to ask questions. After all queries had been satisfied, participants signed an informed consent document, which had been approved by a University Institutional Review Board. Participant provided demographic information and completed the EDSS_{SR} and self-report balance confidence scale (Activity-Specific Balance Confidence Scale – ABC) [19].

Following the completion of surveys, participants completed a standing balance assessment with shoes on. All participants were instructed to stand upright on a force plate with their feet shoulder width apart and hands relaxed by their sides, while their vision was fixated at a target 2 m away. The balance assessment consisted of three unique conditions:

eyes open/firm surface (EO), eyes closed/firm surface (EC), and eyes open/foam surface (FEO). In the FEO condition, a medium density foam pad (15 cm thickness) was placed on top of the force plate. Participants completed each balance assessment condition twice for 30 s each. The eyes closed/foam surface condition was not included in this assessment as the majority of participants could not complete the task in a pilot study. Participants were allowed to rest between trials if necessary, and the test order was fixed (EO-EC-FEO).

Postural sway was simultaneously recorded using two inertial sensors: BioStamp and MTx-49A53G25 mounted on participant's posterior trunk at L5, near the body COM, and by a force plate (FP4060-05-PT-1000, Bertec Corp., Columbus, OH, USA). The MTx sensor was chosen as a reference standard for measuring acceleration during balance assessment since it is a validated measure of postural sway [13, 20]. The BioStamp sensor was applied directly to the skin, while the MTx sensor was located on top of the BioStamp sensor and held in place with an elastic belt. For both sensors, the sensing axes were oriented along the anatomical anterior-posterior (AP), medial-lateral (ML), and vertical directions. The BioStamp sensor had a sensitivity of 10 mg with a measurement range of ± 8 g, and the MTx sensor had a sensitivity of 1.5 mg with a measurement range of ± 5 g.

Force plate data were sampled at 1,000 Hz and low pass filtered (4th order Butterworth) at 5 Hz before center of pressure (COP) displacement was calculated. Acceleration data from both inertial sensors were sampled at 50 Hz, gravity-corrected [21] and low pass filtered (4th order Butterworth) with a cutoff frequency at 5 Hz [7] using a customized MATLAB program (Mathworks, Inc., Natick, MA, USA).

Data Analysis

A set of postural sway metrics were derived from the COP sway data (denoted as COP sway metrics) using established procedures [7]: (1) root mean squared sway amplitude (unit in mm) along the AP (RMS_{AP}) and ML axis (RMS_{ML}); (2) 95% confidence ellipse sway area (CEA – unit in mm^2); (3) sway path length of COP trajectory (SP – unit in mm); (4) mean sway velocity (MV – unit in mm/s); and (5) total power (TP – unit in m^2). This set of metrics was chosen to adequately characterize different aspects of postural control [13, 22, 23].

The same set of metrics was computed from the resultant planar (2D) acceleration measured at the L5 level for both inertial sensors (denoted as BioStamp and MTx sway metrics): (1) root mean squared sway acceleration (unit in m/s^2) along the AP (RMS_{AP}) and ML axis (RMS_{ML}); (2) 95% confidence ellipse sway area (CEA – unit in m^2/s^4); (3) sway path length of acceleration trajectory (SP – unit in m/s^2); (4) mean sway velocity (MV – unit in m/s); and (5) total power (TP – unit in m^2/s^4). In addition, the resultant JERK (unit in m^2/s^5), an indicator of the smoothness of postural sway, was calculated using an established formula [13].

Statistical Analysis

Prior to data analysis, all derived sway metrics were log-transformed to meet the normality request for further analysis. Agreement between the BioStamp and the MTx sensor was analyzed using two distinct approaches: (1) for each trial, cross-correlation coefficient (Xcor) was calculated from the filtered and gravity corrected time series of the acceleration data (AP and ML direction) to evaluate the signal similarity between sensors. (2) Intraclass correlation coefficient ($ICC_{2,1}$) was calculated to determine the agreement between sway metrics derived from BioStamp and MTx sensor. Mean and 95% confidence interval of Xcor and ICC values were calculated across all test conditions. Because the MTx sensor had been extensively validated against the force plate in previous investigations [13, 20], and the primary goal is to validate the BioStamp sensor, once it was determined that BioStamp and MTx had a similar output, only BioStamp sway metrics were compared with the force plate COP sway metrics.

Table 1. Participants' characteristics

	Healthy controls	MS _{Mild}	MS _{Severe}
Number (male/female)	15 (5/10)	19 (4/15)	20 (6/14)
Age, years	57.9 (12.9)	55.9 (11.3)	60.1 (8.0)
MS type	NA	Relapse-remitting (17) Benign (2)	Relapse-remitting (11) Primary progressive (2) Secondary progressive (7)
Years since diagnosis	NA	17.5 (8.5)	20.1 (10.2)
EDSS	NA	3.2 (0.6)	6.2 (0.3)
ABC	95.4 (5.8)	80.6 (20.7)	53.9 (15.6)

All values are mean (standard deviation) unless otherwise noted.

Table 2. Cross-correlation coefficients (95% CI) across all test conditions between BioStamp and MTx acceleration time series

	Anterior-posterior	Medial-lateral
Eyes open	0.91 (0.89–0.92)	0.87 (0.85–0.89)
Eyes closed	0.93 (0.92–0.95)	0.89 (0.86–0.91)
Eyes open on foam	0.94 (0.93–0.95)	0.94 (0.93–0.96)

To determine the similarity between BioStamp and COP sway metrics, the Pearson correlation coefficient was calculated for each sway metric. Correlation threshold was set as poor ($r < 0.5$), moderate ($0.5 \leq r < 0.7$), or good ($r \geq 0.7$) [24]. Two-way linear mixed model (group $\times$ condition) was also performed to determine if the BioStamp sway metric was sensitive to the impact of MS on postural sway similar to COP sway metrics. A Bonferroni pairwise correction ($p < 0.017$) was applied to account for multiple comparisons. Given that an important goal of balance assessment in individuals with MS is to track subtle impairment, stepwise multivariate binary logistic regression was performed to determine if BioStamp sway metrics were able to correctly classify participants as MS_{Mild} or healthy controls with comparable accuracy as COP sway metrics. In this analysis, the population group was used as the dependent variable while sway metrics (i.e., CEA, SP, MV, JERK, etc.) were used as independent variables. Additionally, a univariate binary logistic regression was performed on balance confidence (ABC) scores to determine the classification accuracy of the clinical rating scales. SPSS (version 24, IBM Corp., Armonk, NY, USA) was used for all statistical analyses.

Results

Due to unforeseen technology difficulties, data recorded from 6 trials were discarded. Additionally, 2 MS_{Severe} participants only completed the EO condition due to safety concerns.

Participants' demographic characteristics are presented in Table 1. Overall, there were minimal differences in age and gender composition between groups. Per design, the MS_{Mild} and MS_{Severe} groups were significantly different in self-reported disability (EDSS_{SR}). The

Table 3. ICC_(2,1) between postural sway measurements by BioStamp and MTx sensors

	Eyes open	Eyes closed	Eyes open on foam
Sway JERK	0.98 (0.96–0.99)	0.93 (0.88–0.96)	0.88 (0.80–0.93)
Root mean squared sway acceleration in anterior-posterior direction	0.95 (0.91–0.97)	0.98 (0.97–0.99)	0.99 (0.98–0.99)
Root mean squared sway acceleration in medial-lateral direction	0.98 (0.96–0.99)	0.99 (0.99–0.99)	0.99 (0.97–0.99)
95% confidence ellipse sway area	0.98 (0.96–0.99)	0.99 (0.99–0.99)	0.99 (0.98–0.99)
Sway path length	0.98 (0.97–0.99)	0.97 (0.96–0.99)	0.93 (0.88–0.96)
Mean sway velocity	0.95 (0.91–0.97)	0.99 (0.98–0.99)	0.99 (0.99–0.99)
Total sway power	0.98 (0.96–0.99)	0.99 (0.99–0.99)	0.99 (0.98–0.99)

Table 4. Pearson correlation coefficients (*r*) (95% CI) between postural sway measurements by BioStamp sensor and force plate

	Eyes open	Eyes closed	Eyes open on foam
Root mean squared sway amplitude in anterior-posterior direction	0.84 (0.72–0.90)	0.90 (0.86–0.94)	0.84 (0.73–0.90)
Root mean squared sway amplitude in medial-lateral direction	0.83 (0.72–0.90)	0.89 (0.82–0.94)	0.86 (0.81–0.92)
95% confidence ellipse sway area	0.90 (0.83–0.95)	0.92 (0.86–0.97)	0.89 (0.82–0.94)
Sway path length	0.89 (0.81–0.94)	0.94 (0.91–0.96)	0.85 (0.75–0.93)
Mean sway velocity	0.70 (0.52–0.81)	0.79 (0.66–0.87)	0.77 (0.65–0.86)
Total sway power	0.91 (0.85–0.96)	0.94 (0.91–0.97)	0.89 (0.83–0.93)

All reported correlation coefficients are significant ($p < 0.05$).

MS_{Mild} group included more relapse-remitting MS participants ($n = 17$) in comparison with the MS_{Severe} group ($n = 11$). Significant differences in balance confidence (ABC) ($p < 0.01$) were also observed among all three groups; the MS_{Severe} group reported the lowest and healthy controls reported the highest balance confidence.

The mean and 95% confidence intervals of the cross-correlation coefficient (Xcor) of acceleration time series between sensors are reported in Table 2. High Xcor were observed across all conditions and groups in both AP and ML direction (Xcor ≥ 0.87), indicating significant signal similarity between sensors. ICCs demonstrated an excellent level of agreement between all BioStamp and MTx sway metrics ranging between 0.88 and 0.99 (Table 3). Good to excellent correlation ($r \geq 0.70$) between BioStamp and COP sway metrics were observed in all sway metrics and conditions (Table 4).

Figure 2 displays the mean and standard error of the sway area and total power measured by the force plate and accelerometer as a function of participant group and test condition. Overall, consistent group differences between healthy controls, MS_{Mild}, and MS_{Severe} can be observed across devices. It is also clear that there are a few instances in which the accelerometer sway metrics are unable to differentiate MS_{Mild} from healthy controls and MS_{Severe}. For complete comparison between BioStamp and COP sway metrics, please see the online supplementary Table (for all online suppl. material, see www.karger.com/doi/10.1159/000485958).

Binary stepwise logistic regression was performed to determine which sway metrics were able to correctly classify participants as MS_{Mild} and healthy controls. For Biostamp

Fig. 2. Mean and standard error of sway area and total power measured by force plate and BioStamp as a function of group and condition.

sway metrics, the stepwise logistic regression model identified TP in the EO condition as significant independent predictor to differentiate MS_{Mild} from healthy controls (model $\chi^2 = 5.05$, $p = 0.025$, 82.4% sensitivity, 71.4% specificity). For COP sway metrics, the stepwise logistic regression model also identified TP as significant predictor in the EO condition (model $\chi^2 = 5.79$, $p = 0.016$, 76.5% sensitivity, 78.6% specificity). The overall classification accuracy of the BioStamp sway metric was the same as the COP sway metric in the EO condition (77.4%). COP root mean squared sway amplitude along the AP axis was also identified as significant predictor in the EC condition (model $\chi^2 = 6.26$, $p = 0.012$, 57.9% sensitivity, 50% specificity), yet its classification accuracy (54.5%) was not satisfactory. No significant predictor was identified for the FEO condition. The ABC score, when entered as the sole predictor in the logistic regression model, provided an overall diagnostic accuracy of 76.5%.

Discussion

Various methods have been used to assess balance impairment and tracking the efficacy of therapeutic interventions in clinical populations [25]. However, subtle changes in postural sway are often undetectable using traditional clinical rating scales, while widely used force plate platforms are not feasible outside research settings. Therefore, lightweight body-worn sensors may provide easy-to-use and objective alternatives for balance assessment outside

the research laboratory. This study aimed to establish the validity of a novel lightweight body-worn sensor (BioStamp) to quantify postural stability during a range of postural conditions in individuals with MS.

The current results indicate that this sensor system is suitable for assessing postural stability in MS population. Specifically, acceleration signal and sway metrics recorded from the BioStamp sensor was found to be strongly matched with the validated inertial sensor (MTx). Second, all BioStamp sway metrics were found to be strongly correlated with the gold standard COP sway metrics measured by force plate. Lastly, similar group differences in balance performance between healthy controls and individuals with MS, as well as similar performance in classification accuracy were observed between BioStamp and COP sway metrics.

As expected, across all measurement devices, postural sway increased in the altered sensory inputs condition (i.e., standing on foam; eye closed). Group differences in postural sway between MS participants and healthy controls were consistent with previous reports [9, 14, 15]. That is, individuals with MS swayed more than healthy controls, and their postural sway increased more than that of healthy controls when standing under altered sensory conditions.

Overall, the BioStamp sway metrics were nearly as effective as the COP sway metrics in differentiating individuals with poor balance from healthy controls. More specifically, sway metrics derived from the BioStamp sensor and force plate could consistently distinguish between MS_{Severe} and healthy controls in all test conditions, as shown in Figure 2 and the online supplementary Table. The classification accuracy further confirmed that postural sway in the EO condition is the best test to differentiate MS_{Mild} and healthy controls (77.4%), and comparable with the classification accuracy using validated self-report measures (i.e., ABC scale), whereas postural sway (BioStamp and COP sway metrics) in the EC/FEO conditions were less accurate. Although this observation seems counterintuitive, it is consistent with Solomon et al. [15] who observed that sway metrics quantified with accelerometers were unable to separate mildly impaired individuals with MS from healthy controls in challenging balance conditions. It was speculated that the lack of discrimination stemmed from a uniform increase in postural sway with postural challenge. It also highlights the need for recommendations on the most appropriate conditions to test individuals with MS postural control.

It is worth noting that in the current investigation, the accelerometry sway metrics were derived primarily from the 2D planar acceleration at the approximate COM, and were not directly comparable to the COP displacement sway metrics. Even though the COM displacement can be approximated by twice integrating the acceleration signal, the signal noise and drift could be problematic for true estimation of the orientation and position of the device over time. There is no standard signal processing procedure for reducing the error associated with numerical integration. Therefore, we did not calculate the accelerometry sway metrics from COM displacement. Additionally, the force plate and inertial sensor recording were not hardware synced. Therefore, the absolute agreement of postural sway measured by COM acceleration and COP displacement cannot be directly compared. Future validation studies should be conducted to evaluate the absolute agreement of COM postural sway measured by accelerometer and 3D motion capture. The reliability of using this sensor for postural sway measurement over a period of time should also be investigated. Although this study is focused on quantification of balance impairment in individuals with MS, this device could be applied in other clinical populations with balance impairment (i.e., stroke, Parkinson disease). Additionally, user acceptance could be evaluated with further studies.

Conclusions

In summary, the current study examined the validity of the BioStamp sensor for postural sway assessment in individuals with MS. We demonstrated that this novel sensor is a valid and objective measurement tool for postural sway assessment, as its measurements were strongly correlated with gold standard measurement tools (force plate and externally validated inertial sensor) and capable of distinguishing individuals with MS from healthy controls in a similar fashion to the force plate-based measurement. This novel, lightweight and portable sensor may offer unique advantages in tracking patient's postural performance. Future investigations should examine the feasibility and reliability of these novel sensors across multiple timescales as well as its utility outside a research setting.

Statement of Ethics

Participants gave their written informed consent prior to participation. The study protocol has been approved by the University Institutional Review Board.

Disclosure Statement

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