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Using Accelerometer and Gyroscopic Measures to Quantify Postural Stability

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Context: Force platforms and 3-dimensional motion-capture systems provide an accurate method of quantifying postural stability. Substantial cost, space, time to administer, and need for trained personnel limit widespread use of biomechanical techniques in the assessment of postural stability in clinical or field environments.

Objective: To determine whether accelerometer and gyroscope data sampled from a consumer electronics device (iPad2) provide sufficient resolution of center-of-gravity (COG) movements to accurately quantify postural stability in healthy young people.

Design: Controlled laboratory study.

Setting: Research laboratory in an academic medical center.

Patients or Other Participants: A total of 49 healthy individuals (age = 19.5 ± 3.1 years, height = 167.7 ± 13.2 cm, mass = 68.5 ± 17.5 kg).

Intervention(s): Participants completed the NeuroCom Sensory Organization Test (SOT) with an iPad2 affixed at the sacral level.

Main Outcome Measure(s): Primary outcomes were equilibrium scores from both systems and the time series of the angular displacement of the anteroposterior COG sway during each trial. A Bland-Altman assessment for agreement was used to compare equilibrium scores produced by the NeuroCom and iPad2 devices. *Limits of agreement* was defined as the mean bias (NeuroCom − iPad) ± 2 standard deviations. Mean absolute percentage error and median difference between the NeuroCom and iPad2 measurements were used to evaluate how closely the real-time COG sway measured by the 2 systems tracked each other.

Results: The limits between the 2 devices ranged from –0.5° to 0.5° in SOT condition 1 to –2.9° to 1.3° in SOT condition 5. The largest absolute value of the measurement error within the 95% confidence intervals for all conditions was 2.9°. The mean absolute percentage error analysis indicated that the iPad2 tracked NeuroCom COG with an average error ranging from 5.87% to 10.42% of the NeuroCom measurement across SOT conditions.

Conclusions: The iPad2 hardware provided data of sufficient precision and accuracy to quantify postural stability. Accuracy, portability, and affordability make using the iPad2 a reasonable approach for assessing postural stability in clinical and field environments.

Key Words: concussions, motor function, motor control, biomechanics

Key Points

- The accelerometer and gyroscope within the iPad2 provided data of sufficient quantity and quality to enable accurate evaluation of postural stability.
- The accuracy, portability, availability, and affordability of mobile devices can enable health care providers in various clinical and field settings to evaluate postural stability in athletes.
- To improve clinical outcomes, mobile devices can be a mechanism by which sophisticated biomechanical algorithms are translated to the broader field of athletic trainers and clinical teams treating patients with concussions.
- The accuracy and reliability of mobile devices must be validated before these systems are used to assess cognitive or motor function.

Maintenance of stable posture depends on the efficient processing and integration of information from the visual, somatosensory, and vestibular systems and the modulation of efferent responses by the musculoskeletal system.[1] A decline in postural stability is often a hallmark of advancing age[2–4] and neurologic diseases, such as Parkinson disease[5–7] and multiple sclerosis.[8–10] In addition to neurologic disease, concussion, or mild traumatic brain injury (mTBI), has been well-documented to adversely affect postural stability; however, debate exists about the time course for resolution of balance declines postconcussion.[11–21] Often after concussion, static postural-stability declines are most evident when visual and support-surface conditions are altered.[20] Based on the frequency of postural-stability deficits postconcussion, the recent consensus statement on concussion in sport[22] and the

National Athletic Trainers' Association[23] (NATA) recommended that balance assessment be considered part of baseline testing for athletes and that assessment postconcussion is a "reliable and valid addition" to a multifaceted approach to concussion management.

Current methods for examining postural stability range from sophisticated biomechanical techniques to subjective clinical assessments.[14,24–27] Biomechanics-focused methods, which include force plate and 3-dimensional motion-capture systems, provide the greatest reliability and accuracy in assessing balance.[28] The Sensory Organization Test (SOT; NeuroCom Smart Balance Master; NeuroCom International Inc, Clackamas, OR), which is not a traditional biomechanical assessment, uses aspects of biomechanical techniques through a force-plate–based posturography system that measures center-of-pressure (COP) movements while systematically manipulating visual, somatosensory, and vestibular information. Clinically, the SOT has been shown to be sensitive to functional deficiencies in the visual, vestibular, and somatosensory systems often seen after concussion or mTBI[29,30] and, in turn, has been used to track recovery from concussion and evaluate the effectiveness of rehabilitation.[31,32] The primary outcome of the SOT is the equilibrium score. Assuming a maximum of 12.5° of anteroposterior (AP) sway, the equilibrium score is calculated by subtracting the observed peak-to-peak sway range from this value and dividing the difference by 12.5. Scores range from 0 to 100, with 100 representing *0° of AP sway range* and 0 representing *12.5° or more of AP sway*. Despite its sensitivity and precision, the SOT is limited as a clinical or field evaluation tool by its expense, size, need for trained operators, and lack of portability.[26,33]

A cost-effective and space-effective alternative to systems such as the NeuroCom is attaching inertial sensors (eg, accelerometer, gyroscope) to the body to measure linear and angular kinematics. Whitney et al[26] validated accelerometry methods using measures of planar acceleration of the pelvis and reported a correlation with the sway metric of the SOT. However, their methods were weakened by the postprocessing synchronization of the data, which aligned data from the 2 devices according to optimized correlation values rather than via real-time synchronization. Other researchers[26,33–37] have explored the efficacy of accelerometry-based balance measures; however, no approach has combined the use of an accelerometer and a gyroscope in a commercially available, nondedicated device package and then evaluated its effectiveness in assessing postural stability relative to an accepted clinical system, such as the NeuroCom. The recent inclusion of relatively sophisticated inertial-measurement technologies in consumer electronics devices, such as smartphones and tablet-based computing devices, provides an opportunity to use these devices to objectively assess postural stability in athletes during healthy baseline testing, at diagnosis of concussion, during the return-to-play process, and when determining resolution of concussion symptoms.

The most common clinical test to assess postural stability in athletes is the Balance Error Scoring System (BESS).[14] The complete BESS consists of 6 conditions comprising 3 stances performed on firm and foam surfaces with eyes closed.[14] Whereas the BESS is considered a reliable and valid assessment of postural stability,[38] researchers have questioned the interrater and intrarater reliability of its scoring method[39,40] and have noted floor and ceiling scoring effects that may limit clinical utility.[26,27,41] These reliability concerns may be exacerbated in environments where multiple providers (eg, certified athletic trainers, physicians, and physical therapists) work together to diagnose and treat concussed athletes and make return-to-play decisions. Recent technological advances and the inclusion of inertial-measurement units (ie, accelerometer, gyroscope) in mobile devices may provide a readily available and affordable solution to augment subjective clinical assessments of postural stability with objective and quantitative measures.

Table 1. Demographic Information for Participants (Mean ± SD)

Participants	No.	Age, y	Height, cm	Mass, kg
Total	49	19.5 ± 3.1	167.7 ± 13.2	68.5 ± 17.5
Male	22	18.5 ± 3.1	173.8 ± 13.5	82.4 ± 16.0
Female	27	18.4 ± 3.1	161.6 ± 10.7	57.6 ± 8.5

Therefore, the purpose of our study was to determine whether postural stability could be quantified accurately with data gathered by the embedded accelerometer and gyroscope of the iPad2 (Apple Inc, Cupertino, CA). We compared AP center-of-gravity (COG) sway derived from iPad2 sensor data with output from the NeuroCom SOT for amplitude (equilibrium scores) and real-time displacement goodness of fit (mean absolute percentage error [MAPE]) during performance of the SOT. The identification of an accurate method of assessing postural stability with affordable and portable consumer electronics devices would effectively fill the fundamental gap between inexpensive, subjective clinical tests and more expensive biomechanical measurement techniques and would provide a mechanism to improve continuity of assessment and care across multiple providers.

METHODS

Participants

A total of 49 healthy participants met the inclusion criteria: (1) age from 14 to 25 years, (2) no history of concussion in the 6 months before the study, (3) no known musculoskeletal or neurologic condition resulting in impaired balance or postural stability, and (4) complete SOT and iPad2 data sets. Written informed consent was obtained from the parent or legal guardian of all minors before participation, and the Cleveland Clinic Institutional Review Board approved this project. Participant characteristics are provided in Table 1.

Data Collection

Participants completed the 6-condition SOT[14] on the NeuroCom while wearing a custom-built belt securely holding the iPad2 at approximately sacral height with the screen of the device facing away from the body (Figure 1A). This placement of the iPad2 positioned its sensors as near as possible to the approximate center of mass (COM) during upright stance.[26] The iPad2 contains motherboard-level embedded inertial sensors. Linear acceleration of the device was captured with the embedded 3-axis linear accelerometer (model LIS331DLH; STMicroelectronics,

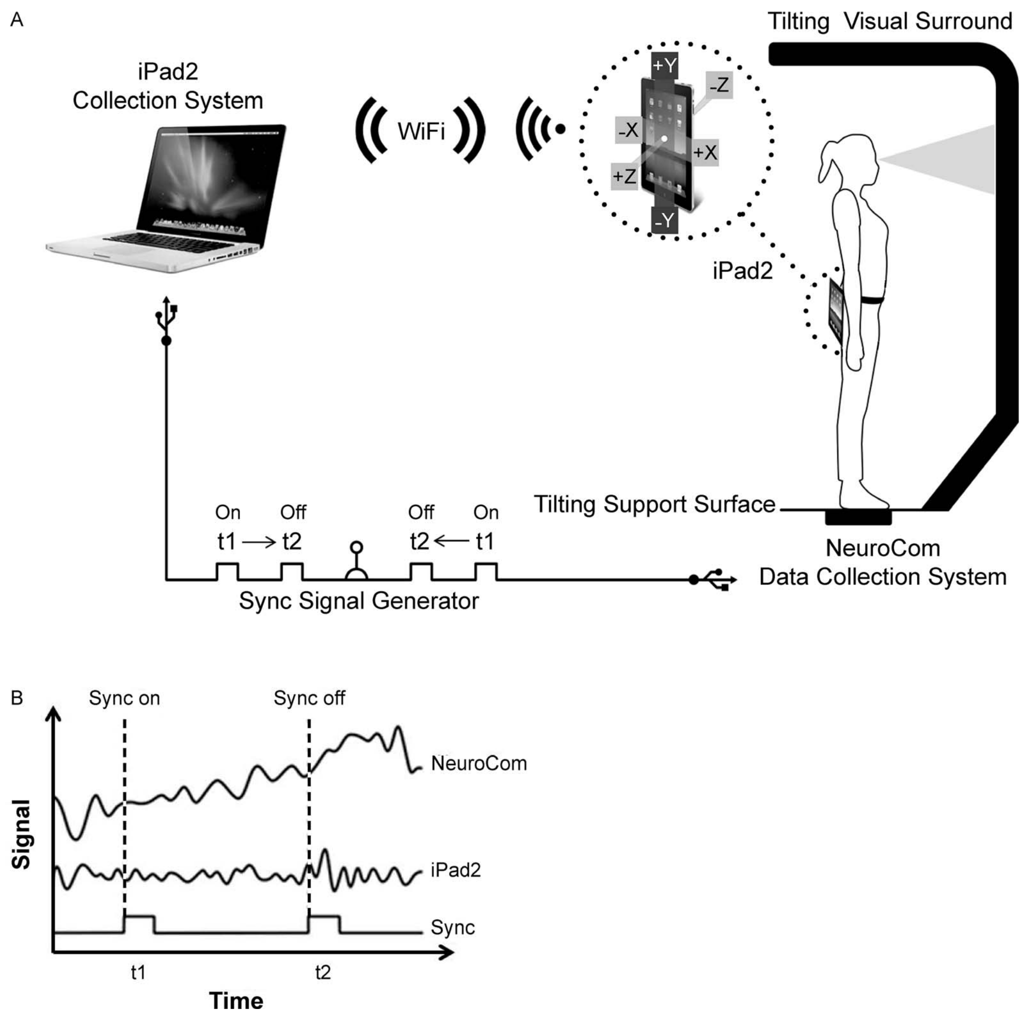

Figure 1. A and B, Experimental setup. Abbreviations: t1, time 1; t2, time 2.

Geneva, Switzerland), which has a range of $\pm 2.0g$, resolution of 0.9 to 1.1 mg, and maximum sampling rate of 100 Hz.[42] Device-rotation rates were measured by the embedded 3-axis gyroscope (model L3G4200D; STMicroelectronics) with a range of $\pm 250°$/s, resolution of 8.75 mdeg/s, and maximum sampling rate of 100 Hz.[43] The Sensor Data iOS application (Sensor Data app by Wavefront Labs; Apple Inc) was used to collect and transmit sensor data from the embedded accelerometer and gyroscope in the x-, y-, and z-directions to a laptop computer (Apple Inc). The coordinate system relative to the device is shown in Figure 1A. We were particularly interested in the x- and z-axes because they are in the direction of the mediolateral (ML) and AP movements, respectively, associated with postural maintenance. The iPad2 data were sampled at 100 Hz, the same frequency as that of the NeuroCom system.

Data were transmitted from the iPad2 with a user-datagram protocol over a WiFi connection to another device. Before data collection, the WiFi connection was established between the iPad2 and a laptop computer, and data were logged and saved continuously on the laptop computer during the trial using a customized LabView data-collection program (National Instruments Corp, Austin, TX). This experimental setup minimized the latency of data transmission between the iPad2 and the laptop computer; only 1 of 882 trials was discarded due to loss of more than 3 consecutive data points. The median number of lost individual data points was 1 per trial (0.05% of total data points). The NeuroCom force plate measures COP in the 2-dimensional plane associated with AP and ML sway. The "On" signal from the NeuroCom indicating the initiation of each trial was collected and processed through an analog-to-digital converter connected to the laptop computer and was used to mark the start of the 20-second trial (Figure 1B). The COP data from the NeuroCom were synchronized with iPad2 data in real time using the same LabView data-collection program. Individual trials were eliminated if any of the following criteria were met: (1) the participant committed a testing error that normally would invalidate the SOT, such as moving the feet midtrial or falling (8 trials); (2) poor data integrity (1 trial); or (3) data-transcription error, such that files with different data sets were mistakenly labeled with the same name (18 trials). The remaining 855 trials, representing 97% of collected trials, were used in the analysis.

Data Analysis

The AP COG angle was used for all outcome metrics. The NeuroCom system measures AP COP for position on the force plate at each time point in a trial, converts it to AP

COG angular sway via a trigonometric relation incorporating the height of the participant, and calculates the equilibrium score metric using Equation 1:

$$\text{Equilibrium Score} = \frac{12.5^\circ - \left[\text{maximum}\left(\text{Sway}_{AP}(\theta)\right) - \text{minimum}\left(\text{Sway}_{AP}(\theta)\right)\right]}{12.5^\circ} * 100\%, \quad (1)$$

where Sway_{AP} is AP sway.

To generate an AP COG sway metric from the iPad2, we used a mathematical model to combine the accelerometer and gyroscope data to best predict the COG sway metric from the NeuroCom system. Specifically, accelerometer and gyroscope data (recorded in $m\cdot s^{-1}\cdot s^{-1}$ and rad/s, respectively) were initially filtered using a fourth-order, low-pass Butterworth filter with a cutoff frequency of 1.25 Hz. To account for initial orientation of the device on the patient's lower back, accelerometer fields were offset by the mean of the first 10 samples (0.1 seconds) of the trial. Rotation-rate data were integrated once to provide rotational displacement in degrees. Using a nonlinear mixed-effects model, iPad2 sensor data were fit to the COG sway-angle output from the NeuroCom. Before fitting, we filtered the COG sway-angle data from the NeuroCom system with the same low-pass filter used on the iPad2 data. The resulting function, a 5-knot restricted cubic spline and a sine function, was the mathematical model for predicting COG movement in the AP plane using the iPad2 inertial sensor data.

The accuracy of the modeled COG sway angle from the iPad2 data was evaluated in 2 ways. First, the maximum and minimum predicted values were compared between the 2 devices using the SOT equilibrium scores. The NeuroCom equation used for the equilibrium score calculation is shown in Equation 2:

$$\text{COG AP sway(deg)} = \arctan\left(\frac{\text{COG AP position (cm)}}{.55*\text{participant's height (cm)}}\right) * \frac{180^\circ}{\pi} \quad (2)$$

For comparison, the equilibrium scores from the NeuroCom system were exported directly, and the modeled COG sway data from the iPad2 sensors were used in Equation 2 to calculate the iPad2 equilibrium scores. Equilibrium scores from the NeuroCom and the iPad2 sensors were evaluated for goodness of fit via Bland-Altman plots, treating each trial as a separate observation. In this approach, the differences between the equilibrium scores calculated by the NeuroCom and iPad2 were subtracted from each other (ie, NeuroCom − iPad2) to quantify the measurement error and were plotted against the average of the equilibrium scores from the 2 devices, which represented the best approximation of the "true" equilibrium score. The mean and standard deviation (SD) of the differences then were determined. The *limits of agreement* were defined as mean ± 2 SD and represent the limits within which one can be 95% confident the measurement error resides. The mean of the difference and the respective limits of agreement are reported for each SOT condition.

We used the MAPE to assess how well the time-series data of the AP COG sway-angle data from the iPad2 and NeuroCom systems tracked each other on a sample-by-sample basis. The filtered AP COG sway angle of the NeuroCom and the modeled AP COG sway of the iPad2 were used in the analysis. The MAPE values range from 0 to infinity, with larger values representing greater error.[44] For each COG sway data point in a trial, the absolute difference or error between the NeuroCom and the iPad2 COG sway metric was divided by the measured value (NeuroCom) and multiplied by 100. The MAPE value then was calculated as the mean value of this metric across all samples within a trial. We collapsed the MAPE values across trials within a condition and participant. In addition to the MAPE, the true error between the NeuroCom and iPad2 COG sway angle was calculated across all samples in each trial. The median error across all samples is reported. All offline analyses were performed using custom scripts in MATLAB (The MathWorks, Inc, Natick, MA).

Sex and age differences were evaluated on the averaged SOT equilibrium score in each condition using linear random models for the iPad2 and NeuroCom and R software (R Project for Statistical Computing; Institute for Statistics and Mathematics of Wirtschafts Universitat Wien Vienna University of Economics and Business, Vienna, Austria). The α level was set at .05.

Table 2. Equilibrium Scores From Our Study Compared With Scores Reported by Wrisley et al[46]

Sensory Organization Test	Mean ± SD Equilibrium Score: Wrisley et al[46] (N = 13)[a]	Mean ± SD Equilibrium Score: Our Study (N = 49)[b]	*P* Value
Condition			
1	95.3 ± 1.6	95.3 ± 1.9	>.99
2	93.6 ± 2.2	93.0 ± 2.4	.40
3	91.6 ± 4.0	91.4 ± 4.1	.87
4	87.3 ± 6.0	89.8 ± 6.5	.22
5	74.6 ± 3.6	71.0 ± 10.9	.25
6	72.9 ± 7.1	78.3 ± 10.3	.08
Composite score	83.4 ± 3.0	84.0 ± 3.1	.54

[a] The mean ± SD age of participants was 24 ± 4 y.
[b] The mean ± SD age of participants was 19.5 ± 3.1 y.

RESULTS

Sex and age were not predictors of the equilibrium score in any SOT condition (SOT-1 through SOT-6; $P > .05$ for both predictors in all conditions) for either the iPad2 or NeuroCom systems. Therefore, we collapsed data across age and sex for all other analyses. The equilibrium scores calculated by the NeuroCom for our sample were not different from data reported previously (Table 2).[45,46]

Grouped equilibrium scores (mean ± SD) from the NeuroCom and iPad2 are provided for all trials in Figure 2A and B. Bland-Altman plots revealed that the mean difference (bias) in equilibrium scores for each condition was close to 0, with SOT-1 showing the smallest (0.01%) and SOT-5 showing the largest (–6.2%) mean difference (Figure 2C through H). For all other conditions except SOT-5, the mean difference was equal to or less than 2.6% (Table 3). Using Equation 1, even the largest mean difference in equilibrium scores between the 2 devices (–6.2% in SOT-5) represented a small discrepancy in actual sway angle (ie, less than 1°).

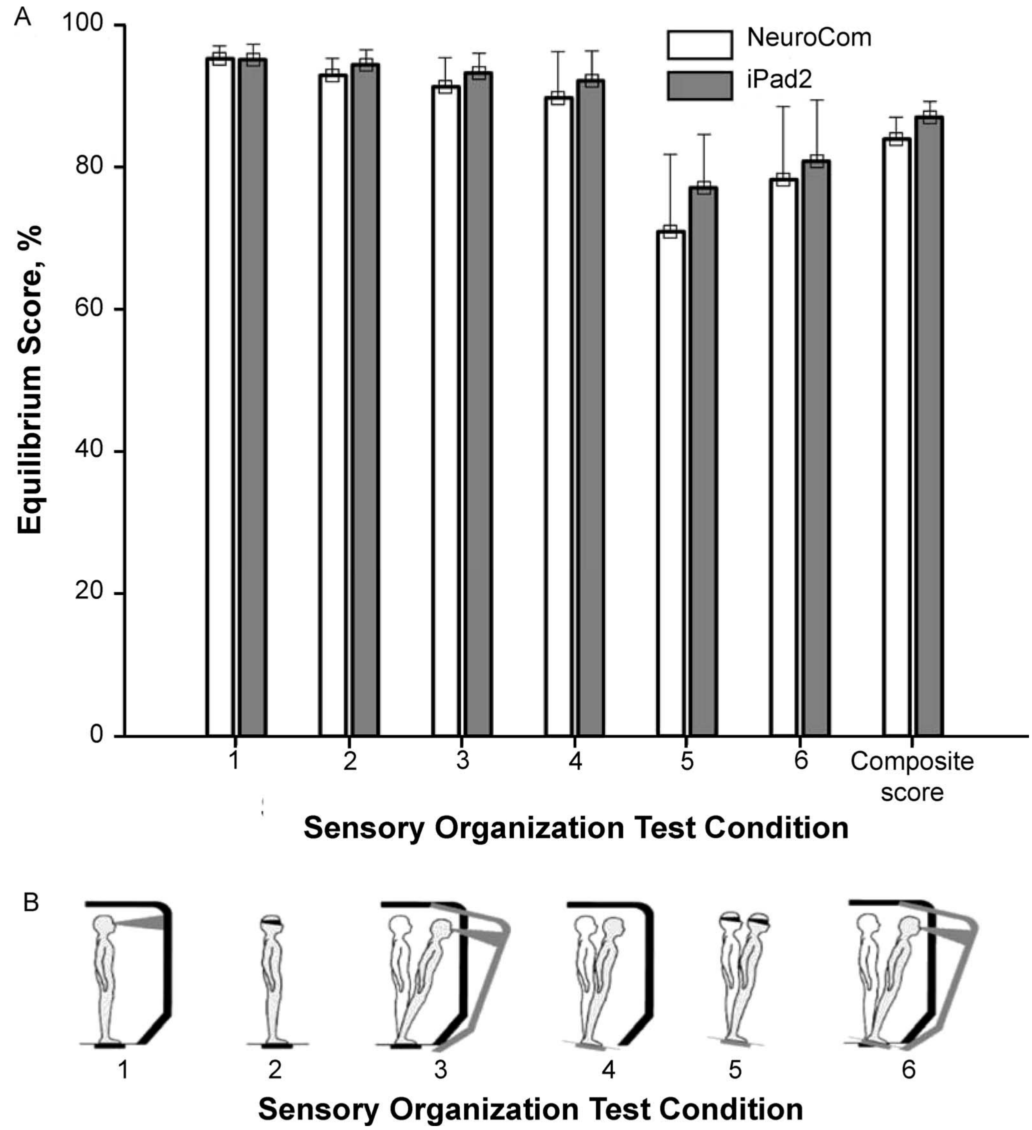

Figure 2. A, Equilibrium scores (mean and standard deviation values) from NeuroCom Sensory Organization Test (SOT) and calculated from iPad2 (Apple Inc, Cupertino, CA) sensor data are shown for the 6 SOT conditions and composite score. B, The 6 SOT conditions are illustrated (adapted with permission from NeuroCom International Inc, Clackamas, OR). C–H, Bland-Altman plots for each SOT condition, where the difference in equilibrium scores (NeuroCom – iPad2) is plotted against the average 2 equilibrium scores on a trial-by-trial basis. The solid lines represent the mean difference in equilibrium scores, where a score closer to 0 indicates more similarity in the values from the 2 devices. The dashed lines represent the upper and lower limits of agreement (mean difference ± 1.96 SD of the difference in equilibrium scores), where a smaller gap between the dashed lines indicates less variability and more consistency across most of the values from the 2 devices. Continued on next page.

Additional inspection of the limits of agreement in the Bland-Altman plots also revealed that 95% of the measurement error between the 2 devices was from –3.8% to 4.0% or from –0.5° to 0.5° in the condition of best agreement (SOT-1) and from –23.1% to 10.7% or from –2.9° to 1.3° in the condition with the poorest agreement (SOT-5; Table 3). Extrapolating from this result, the largest absolute value of the measurement error within the 95% confidence intervals for all conditions was 23% or 2.9°. Further inspection of Table 3 shows that for most conditions (SOT-1 through SOT-4) the largest absolute value of the measurement error in the 95% confidence intervals was 11% or at most 1.4°.

Four representative trials with MAPE values ranging from 0.68% to 4.53% are depicted in Figure 3. Visual inspection of Figure 3 indicates that the iPad2 measurements tracked the NeuroCom COG measurement very closely for small, rapid movements (Figure 3A and B) and for large movements (Figure 3C and D) in the time domain while also capturing the extreme values within each trial. The MAPE metric, which was used to quantify the goodness of fit between the iPad2 and the NeuroCom COG time-series data, was 7.93% for the entire cohort, signifying that the COG value predicted with the iPad2 sensor data was similar to the NeuroCom COG measurement across all trials. Furthermore, the model had a median difference of –0.01° (first and third quartiles = –0.27° and 0.24°, respectively) between iPad2 and NeuroCom measures of COG sway. Table 4 shows MAPE per condition for all analyzed trials. The SOT-5 had the smallest MAPE value (5.87%), representing the lowest error and best fit between the iPad2 and NeuroCom COG sway metrics despite having the largest peak-to-peak movements (Table 3). The SOT-2 had the

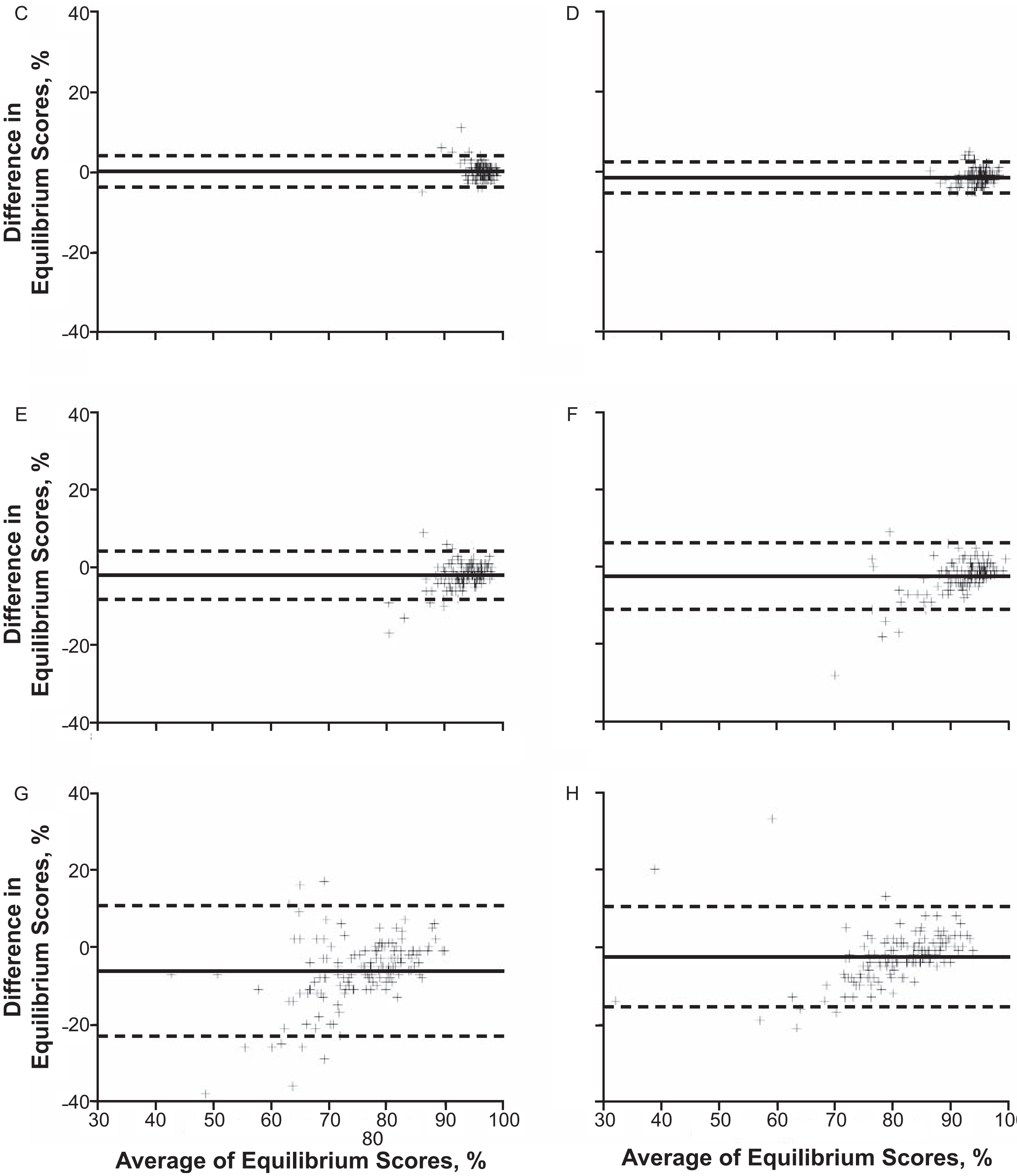

Figure 2. Continued from previous page.

largest MAPE value (10.42%) and, based on the equilibrium score metric (Table 3), the smallest sway range.

DISCUSSION

Comparison between the NeuroCom- and iPad2-generated equilibrium scores indicated that postural stability can be quantified accurately in healthy adolescents and young adults using data from the accelerometer and gyroscope embedded within the iPad2. The Bland-Altman analysis assessed the ability of the iPad2 to accurately capture the peak-to-peak sway magnitude within a trial as quantified by the equilibrium score. The SOT-1 had the smallest spread between the 95% confidence intervals (mean bias = 0.01%;

Table 3. Results From Bland-Altman Analysis

Sensory Organization Test Condition	Mean Difference in Equilibrium Scores Between the Devices		
	Mean Bias, %	Limits of Agreement, %	
		Lower	Upper
1	0.01	−3.8	4.0
2	−1.5	−5.3	2.3
3	−2.0	−8.3	4.4
4	−2.4	−11.0	6.2
5	−6.2	−23.1	10.7
6	−2.6	−15.6	10.4

limits of agreement = –3.8%, 4.0%), and the trial with the smallest mean measurement error was in this condition. Overall, the iPad2 consistently provided a measure similar to the NeuroCom system during a condition in which very minute balance movements were made. The largest mean measurement error was in SOT-5, which also had the largest span between the 95% confidence intervals (mean bias = –6.2%; limits of agreement = –23.1%, 10.7%). Even in the most difficult balance condition, the mean bias and the limits of agreement represent less than 1° and 2.9°, respectively, of sway difference between the 2 devices.

Overall, the Bland-Altman analysis highlighted the low measurement error using the iPad2 when the peak-to-peak sway magnitude of a trial was small (ie, average equilibrium scores >80 in Figure 2C through H, all conditions). We do not believe this is a limitation of the iPad2 sensors themselves but of the limited variability in the dataset. In 70% of all the trials from all conditions, the peak-to-peak sway magnitude was equal to or less than 2°, measured as NeuroCom equilibrium scores equal to or greater than 84. Given that the statistical model that generated the sway estimate of the iPad2 was based on this well-performing dataset, the model could predict good performance (ie, most of the dataset) very well and had more difficulty and measurement error when estimating poor performance. Particularly in SOT-5 and SOT-6, when test conditions were more challenging and elicited more sway and variability in the performances, the measurement errors of the peak-to-peak sway values were increased and more variable. Our study indicated that data from the sensors within the iPad2 can predict time-series sway position without sacrificing accuracy in quantifying peak-to-peak sway displacements for most trials in the studied population. Once we have additional data in other populations or those after concussion, with the anticipated increased variability in performance, the statistical model will adapt to better capture larger peak-to-peak sway values.

The iPad2 sensors accurately tracked the NeuroCom real-time COG sway in all SOT conditions as measured by the MAPE values and the median difference between the NeuroCom and iPad2 measurements. The accuracy of the model was evaluated with the MAPE metric, giving a relative percentage value that signified the "error" of the predicted value from the actual value. The MAPE values were smallest during SOT-3 through SOT-6 despite the much higher amplitude and volatility of balance reactions by the individual. The less demanding tasks (SOT-1 and SOT-2) had larger but still relatively small MAPE values. Furthermore, the absolute median difference between the predicted iPad2 and the actual NeuroCom COG sway angles was very close to 0 (median difference = –0.01°). These results are timely because evidence suggests that whereas the accurate characterization of AP peak-to-peak range of sway has clinical utility, the tracking and quantification of balance reactions throughout an entire trial may be a source of added sensitivity.[47] In future studies, including cross-correlation analyses of the real-time sway data may provide even better agreement between the 2 devices than what we reported.

Whereas posturography methods estimate COG sway via ground reaction forces[48] to quantify postural stability, inertial measurements aim at characterizing sway relative to COM. From a methodologic standpoint, the placement of the iPad2 at the sacrum reasonably approximated COM position, which was important for an accurate characterization of body sway when using accelerometry.[31] The iPad2 measures linear acceleration and angular rotation independent of gravitational effects in 3-dimensional space via an embedded triaxial accelerometer and gyroscope. Within traditional inertial-measurement methods, sway-angle measurements using linear accelerometers may not provide the best estimate of stability when COM motion becomes less planar and more angular with rotation about the ankle joint.[26] In these cases, gravitational effects become large and affect axial-acceleration measurements.[26] Incorporation of the triaxial gyroscope allows rotation to be measured, which is particularly useful when sway is less planar and larger movements are made, as evidenced by greater correlation of equilibrium scores in the more challenging SOT conditions (ie, SOT-3 through SOT-6). Whereas the utility of commercially available sensor hardware, such as that built into the iPad2, has not been investigated systematically in a clinical environment, the specifications of the sensors and methods used were consistent with the sophisticated and single-purpose balance-assessment and movement-assessment devices and techniques.[26] As sensor specifications and processing rates continue to improve with new tablet-device hardware, the resolution of these techniques will become more precise. In addition, consumer electronic devices, such as tablets and smartphones, offer vast opportunities for developers and users to create custom, nonproprietary applications that can be shared across investigators to facilitate the collection of a common group of data elements for population-based studies. These types of devices offer the possibility of providing a complete, portable tool for collecting, processing, and analyzing clinical assessments of postural stability, unlike stand-alone inertial sensors. Whereas the NeuroCom SOT improves our understanding of the balance declines associated with concussion, it is not feasible or practical for use in most environments in which athletic trainers practice due to extensive cost, space, and personnel requirements.

Given that we have shown the validity of using the embedded sensors of the iPad2 to assess postural stability, we have opened an additional avenue of investigation that involves quantification of movements in real time in more than the AP direction. This is possible with the 3-dimensional inertial sensors of the iPad2. The triaxial accelerometer and gyroscope allow the expansion of balance evaluation to a more comprehensive quantification of COM movement in 3 dimensions (AP, ML, and trunk

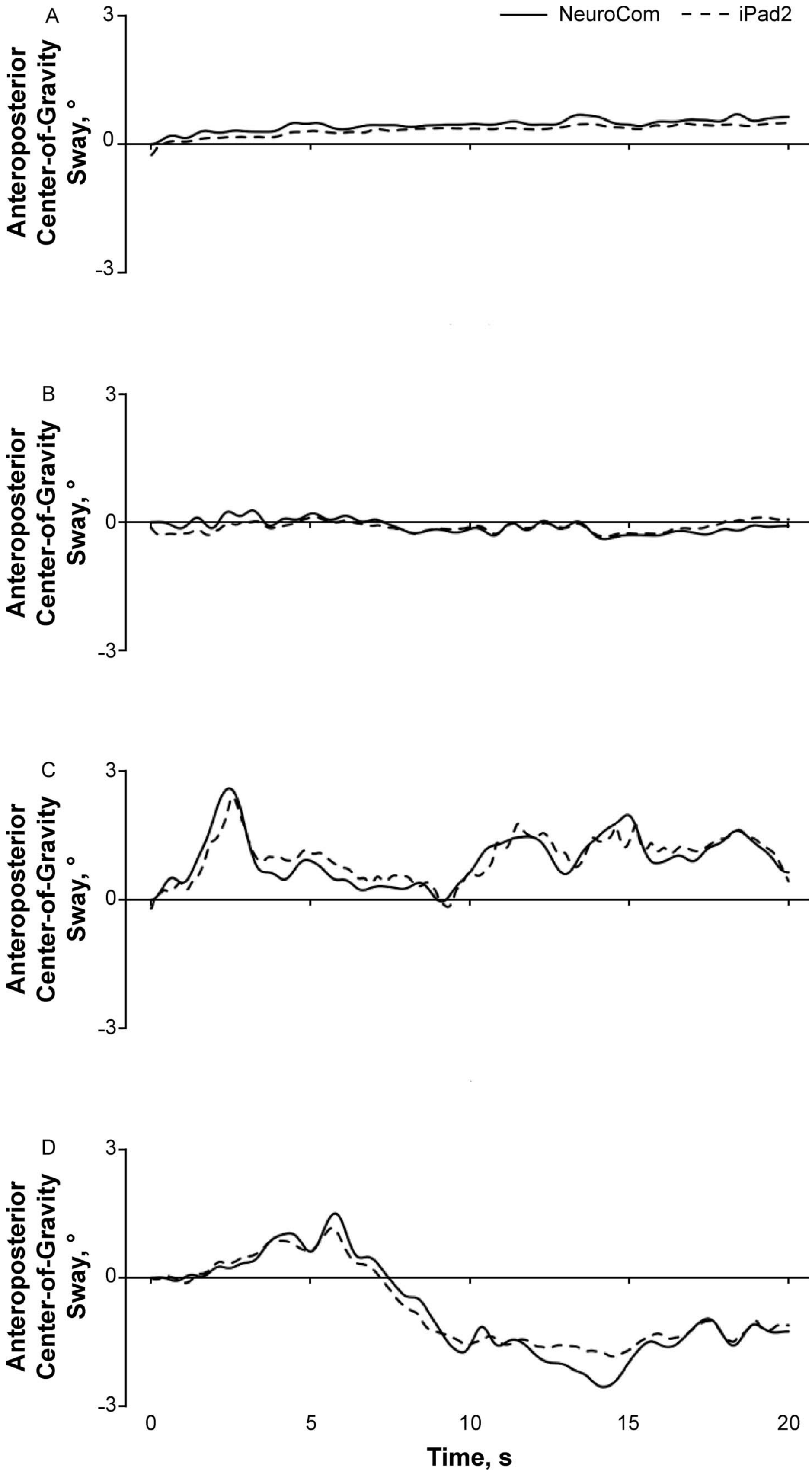

Figure 3. Example of real-time anteroposterior center-of-gravity sway data from NeuroCom (NeuroCom Smart Balance Master; NeuroCom International Inc, Clackamas, OR) and iPad2 (Apple Inc, Cupertino, CA), with corresponding mean absolute percentage error values for 4 randomly sampled trials: A, Sensory Organization Test (SOT) condition 1; B, SOT condition 4; C, SOT condition 5; and D, SOT condition 6. Positive anteroposterior center-of-gravity sway values correspond to movements in the anterior direction and negative values correspond to movements in the posterior direction relative to the center of gravity. The mean absolute percentage error values were used to determine the goodness of fit for the iPad2 data relative to NeuroCom data and are provided for each condition in Table 4.

Table 4. Overall Mean Absolute Percentage Error Values Per Condition for Center-of-Gravity Sway Time-Series Data From iPad2[a] and NeuroCom[b] Systems

Sensory Organization Test Condition	Mean Absolute Percentage Error ± SD, %
1	9.34 ± 5.46
2	10.42 ± 6.87
3	7.40 ± 5.08
4	8.42 ± 6.30
5	5.87 ± 4.80
6	6.25 ± 4.62
Overall	7.93 ± 5.76

[a] Apple Inc, Cupertino, CA.
[b] NeuroCom Smart Balance Master; NeuroCom International Inc, Clackamas, OR.

rotation). Assessment of postural control, taking all 3 dimensions into consideration, provides a more precise and objective assessment of motor functioning. Multidirectional characterization of balance may be particularly important for optimizing the clinical management of athletes with lingering balance dysfunction by identifying vestibular, neuromuscular, and musculoskeletal deficiencies and providing guidance for the rehabilitative management of patients. We fully acknowledge that this model of balance assessment cannot replace the ability to systematically manipulate afferent inputs to distinguish among somatosensory, vestibular, and visual contributions to postural stability as provided by the NeuroCom. If the ability to distinguish among the various systems that contribute to balance is a goal for future uses of this technology, the development and validation of protocols and additional, more inexpensive equipment to create those conditions is necessary.

Based on strong agreement between equilibrium scores from both devices across SOT test conditions and low error in predicting time-series sway position as evaluated by the MAPE metric, this approach successfully provided a viable measure of postural stability in a cohort of healthy young adults that could be used to assess baseline levels of postural stability as part of a preseason evaluation, as recommended in the recent position statement on concussion from the NATA.[23] In an early publication, Guskiewicz et al[20] correctly noted that most clinicians did not have access to biomechanical laboratories or postural-stability systems for the proper assessment of how concussion may be affecting balance. Thus, in the absence of balance testing, they recommended a conservative strategy for returning athletes to participation. A lack of postural-stability measures led to the development of the BESS for the field and clinical evaluation of balance during preseason baseline testing, postconcussion, and when tracking recovery. Unfortunately, although many advances have been made in the assessment of various aspects of cognitive functioning and better classification of concussion-related symptoms, the objective quantification of balance remains largely subjective via BESS testing for most certified athletic trainers, physicians, and physical therapists. The accurate and reliable assessment of postural stability in a cohort of healthy young adults, similar to the population most often experiencing sport-related concussion, potentially can dramatically improve the treatment and management of concussion. Minimizing the subjectivity of assessment across the multidisciplinary team of providers involved in the care and treatment of concussion by using objective measures will provide clinicians with a more precise method of evaluating motor function. This approach, which is affordable and scalable, can provide new and unique information about the effects of concussion on balance and its recovery. We recently completed a project in which the balance module of the Cleveland Clinic Concussion App (Cleveland Clinic, Cleveland, OH) was used to augment the error scoring of the BESS in a group of healthy and concussed athletes.[49]

Whereas the BESS is currently the preferred clinical assessment of postural stability postconcussion, the development of a portable and sophisticated method of quantifying postural stability opens the possibility of using potentially more sensitive and challenging dynamic testing protocols.[11,50–53] Researchers[52] using more dynamic assessments of postural stability postconcussion have noted that, in some athletes, declines in balance may last from 10 to 30 days postconcussion; investigators[20,54] using static tests have reported that most balance declines are resolved within 3 to 5 days postconcussion. Although dynamic tests of postural stability may be more sensitive than static tests, they are susceptible to the same, if not greater, bias as subjective rating scales because the rater must monitor and evaluate multiple degrees of freedom and potentially manage a more complex scoring schema and rubric. The development of mobile applications capable of objectively quantifying postural stability during dynamic-balance tasks will provide a pathway to their use in athletic or clinical environments. Providers will then be better informed about the true postural-stability capabilities or impairments of athletes suspected to have concussions and better able to assess and treat athletes with lingering balance impairments.

A potential limitation of this study is that the sample included only healthy individuals rather than populations with neurologic conditions or concussions. Although we considered including these populations, our fundamental goal was to determine whether this tablet device provided data that could be used to accurately quantify postural stability. Including a population with neurologic conditions or concussion would have added more variance to the data, which would have compromised our ability to systematically address this question. Given that this approach has been validated, we are conducting large-scale, population-based studies in athletes with concussions (eg, baseline testing and immediate postconcussion through return to play) and populations with neurologic conditions (eg, Parkinson disease, multiple sclerosis). Furthermore, we are evaluating the use of the balance module of the Cleveland Clinic Concussion App to estimate postural stability during more dynamic-stability tasks (eg, tandem gait) and dual-task paradigms (eg, balance plus cognitive tasks) in healthy and concussed athletes. These studies represent the next phase to improve our understanding of how concussion affects dynamic postural stability, dual-task performance, and the recovery of these functions postconcussion in a large population. In these projects, we are using measures of sway in the AP, ML, and trunk-rotation planes to provide 2- and 3-dimensional characterizations of postural stability.

A possible limitation from an analytical perspective is the use of average peak-to-peak sway within a trial. The model relating the iPad2 and NeuroCom data sets was based on the range of values that was recorded in this cohort; overall minimum and maximum sway angles in this group were –7.8° and 10.2°, respectively. It is unclear how well the model would perform on trials with data outside of these values. However, this limited range is not a major concern considering that the limits of stability cited by the NeuroCom SOT are 5° and 7.5° in the posterior and anterior directions, respectively.[55] We anticipate that limitations inherent to many clinical balance tests, such as reliability of scoring and ceiling and floor effects, can be mitigated or eliminated by testing individuals while they perform various tasks or stances.

CONCLUSIONS

To our knowledge, we are the first to evaluate the accuracy of a mobile device against a clinically accepted method of assessing postural stability under a range of conditions. Overall, the results presented here indicate that the accelerometer and gyroscope within the iPad2 provided data of sufficient quantity and quality to enable accurate evaluation of postural stability. Mobile devices, which have continued to decline in cost and increase in availability and hardware capability, are ideally suited to rapidly enable the field of providers associated with concussion management (eg, athletic trainers, physicians, physical therapists) to meet the recommendations set out in the NATA's recent position statement on the management of sport concussion.[23] As mentioned in this position statement, assessment of motor control is an integral part of the concussion baseline and postinjury examination. To understand motor-control processes, objective and quantitative methods using biomechanical principles to characterize movement are necessary. Mobile devices equipped with inertial-measurement hardware provide an opportunity to transition these devices from expensive electronic notebooks into data-collection devices that can aid in understanding motor-control processes. The widespread availability of mobile devices provides individuals practicing in rural or under-served locations with minimal resources an opportunity to evaluate athletes in an objective and quantitative manner that previously was available only to individuals in large academic or medical environments with sophisticated and expensive biomechanical equipment. We are not advocating that mobile devices replace biomechanical analyses, but they can be the mechanism by which sophisticated biomechanical algorithms could be translated to the broader field of athletic trainers and clinical teams treating concussion to improve clinical outcomes.

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We have filed an invention disclosure form to protect the intellectual property that is associated with the metric used in this study.

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