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ORIGINAL RESEARCH

Normative data for the Balance Tracking System modified Clinical Test of Sensory Integration and Balance protocol

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Purpose: Force plate balance testing technology has traditionally been underutilized in clinical and research settings due to the high cost and lack of portability. A relatively new force plate called the Balance Tracking System (BTrackS) has been developed to overcome these barriers. BTrackS recently implemented the modified Clinical Test of Sensory Integration and Balance (mCTSIB) as a means of evaluating various sources of sensory information for postural sway control. The present study aimed to provide much needed normative data for the BTrackS mCTSIB protocol.

Materials and methods: Data from 604 healthy adults (308 women; 296 men) between the ages of 18 and 29 years were collected according to the BTrackS mCTSIB protocol. The protocol consisted of four, 20-second static standing trials that manipulated relative contributions of the vision, proprioception and vestibular sensory systems through various eyes open/closed and foam/no foam conditions. Comparisons of men versus women and the impact of body size (ie body mass index) were determined so that relevant percentile rankings could be calculated.

Results: Analysis of variance showed an interaction between sex and task condition on the BTrackS mCTSIB ($p<0.001$). This interaction indicated that women outperformed men on all conditions, but especially in the fourth trial where eyes were closed and standing was done on a compliant foam surface. Percentile rankings were calculated based on sex and BTrackS mCTSIB condition. No relationship was found between BTrackS mCTSIB results and body size.

Conclusion: Normative data provided in this study are vital for establishing potential sensory feedback-based balance dysfunctions that may exist clinically or in laboratory settings. In addition, this data can aid in the tracking of changes over a rehabilitation period and/or the effectiveness of balance interventions.

Keywords: postural sway, BTrackS, reference values, force plate, center of pressure

Introduction

Standing balance can be defined as the ability to maintain upright posture on two feet without falling. Commonly viewed as a "motor" skill, standing balance actually relies to a large extent on three sensory systems: proprioception, vision and vestibulation. With respect to proprioception, balance information is relayed from skin, muscle and joint receptors providing, primarily, a representation of ankle joint position changes associated with body sway.[1] The visual system, on the other hand, inputs information on head position relative to the surrounding environment, which can be used in a feedforward fashion to anticipate a loss in balance.[2] In contrast, the

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vestibular system serves as an internal conflict resolution system between the head and environment that is absent of external cues. Specifically, vestibular feedback provides an inertial gravitational reference system regarding head positional equilibrium.[3]

Measurement of postural sway is a common means of assessing standing balance in both clinical and laboratory settings. Postural sway is defined as a mechanism whereby sustained oscillatory motion occurs about a fixed postural position.[4] The gold standard for measuring postural sway is via a medical device called a force plate. Force plates quantify postural sway using a metric called center of pressure (COP). COP can be calculated as the weighted average of forces applied to a force plate while standing upon it. Increased COP magnitude (ie greater postural sway) during quiet standing is found in many clinical conditions including multiple sclerosis, mild traumatic brain injury and stroke.[5–7]

Despite the established efficacy of force plate balance assessments, widespread use remains limited due to the high cost and lack of portability associated with most devices. Indeed, some traditional force plates cost in excess of $100,000 and weigh greater than 50 kg. These practical limitations were the impetus for developing the Balance Tracking System (BTrackS). BTrackS is a force plate balance testing solution that is both affordable (<$2,000) and portable (<6.8 kg) compared to its counterparts. BTrackS also promotes a number of time efficient and user-friendly protocols that accurately and reliably examine postural sway.[8,9] One of the most popular protocols is the modified Clinical Test of Sensory Integration and Balance (mCTSIB). The mCTSIB is a derivative of the CTSIB, which was originally developed by Shumway-Cook and Horak.[10] The CTSIB was created to evaluate the contribution of various sources of sensory information for balance.

The mCTSIB utilized by BTrackS objectively measures postural sway in each of four test conditions. The first condition is the "standard" test condition where all three sensory systems (ie proprioception, vision and vestibular) are available to assist in maintaining balance and, therefore, the smallest amount of postural sway is expected. In condition two, the eyes are closed to temporarily eliminate visual feedback, thus, increasing reliance on proprioceptive and vestibular systems. Since proprioception is more heavily utilized for balance than the vestibular system, the typical perspective is that this condition largely measures the contribution of proprioception to balance.[3] In the third condition, the visual and vestibular systems are available, but the proprioceptive system is compromised by having the individual being tested stand on a compliant foam surface. If there is a difficulty maintaining postural sway in this condition, the visual system is typically implicated given its preference over vestibular feedback for balance. In the fourth condition, the eyes are closed and the individual stands on foam. In this case, the visual and proprioceptive systems are compromised, shifting reliance to the vestibular system as the primary sensory source used to maintain balance.

When assessing postural sway in either clinical or research settings, it is vital to have normative data to aid in the interpretation of results. Specifically, comparing test results to typical individuals assists in establishing whether or not a balance dysfunction exists. Additionally, normative data can be used to track positive and negative changes over the course of a rehabilitation or intervention period, helping establish effectiveness of a given treatment. Lastly, as it pertains to the BTrackS mCTSIB protocol, normative data can aide clinicians and researchers in determining the locus of a balance impairment (ie proprioceptive, visual and/or vestibular) through differential diagnosis.

The aim of the present study, therefore, was to establish the first set of normative data for the BTrackS mCTSIB protocol. This was accomplished by collecting BTrackS mCTSIB results from a large sample of healthy young adults and calculating true percentile rankings stratified by relevant sex and body size factors. It was hypothesized based on previous literature that significant differences in performance would be seen showing less postural sway (ie better balance) in women versus men.[11] In contrast, it was expected that no relationship would be seen between body composition and mCTSIB results in any test condition.[11] Overall, the results of this work provide an important resource for a growing cohort of clinical practitioners and research scientists using the BTrackS mCTSIB protocol.

Material and methods

Participants

In this study, data were collected from 604 healthy adults (308 women, 296 men) between the ages of 18 and 29 years (average ± SD=22.7±2.8 years). Participants gave written, informed consent and self-reported having no known balance impairment at the time of testing. Tests were conducted across multiple sites including health fairs, physical therapy clinics, fitness gyms, religious settings and educational institutions, among others. Ethical approval for this human subjects-based research was obtained through the institutional review board of Oakland University, and all procedures adhered to the Declaration of Helsinki and included written informed consent.

Experimental setup

The BTrackS mCTSIB was conducted using the BTrackS Balance Plate and BTrackS Assess Balance software (Balance Tracking Systems, San Diego, CA), which are depicted in Figure 1. The BTrackS Balance Plate is a lightweight force plate that is a registered medical device with the US Food and Drug Administration. The force plate measures 0.4×0.6 m and has been ecologically validated in prior research.[8] A converging body of evidence also exists showing that the BTrackS Balance Plate displays excellent accuracy and precision for the measurement of COP.[12–14]

BTrackS Assess Balance software (version 4) was installed on multiple computing devices (ie laptops and tablets), each running a full version of the Microsoft Windows operating system. The BTrackS Assess Balance software provided an on-screen interface for profile creation, test administration and result interpretation related to the mCTSIB. Due to the user-friendly nature of BTrackS Assess Balance, minimal training was required to learn how to administer the BTrackS mCTSIB protocol. In this case, test administrators became proficient after performing several tests under the guidance of an experienced user.

Testing procedures

Each testing session was conducted in an isolated space with limited distractions. To start each testing session, the BTrackS Balance Plate was leveled on a hard surface, using built-in height adjustable legs. The BTrackS Balance Plate was then connected to the computing device via a USB interface, which also provided power to the plate. Standardized instructions were read to participants, according to the following on-screen script:

> You are about to perform a Clinical Test of Sensory Integration and Balance or CTSIB. The CTSIB consists of four, 20-second trials that measure your ability to control body sway when sensory feedback is systematically manipulated. For each trial, you will stand as still as possible on the BTrackS Balance Plate with your hands on your hips and feet shoulder width apart. You will hear a tone at the beginning and end of each trial. Your CTSIB results will be based on the Center of Pressure (COP) path length from the forces you place on the BTrackS Balance Plate during standing. Sensory feedback will be manipulated by having you close your eyes or stand on foam in some conditions.

In line with the above instructions, participants stood on the plate for four testing trials (one in each of four

Figure 1 Testing materials for this study included the BTrackS Balance Plate (right) and BTrackS Assess Balance software running on a laptop (left).
Abbreviation: BTrackS, Balance Tracking System.

conditions) with their feet shoulder width apart and hands on their hips (Figure 2). The first trial (ie Standard condition, Figure 2A) was conducted with the eyes open while standing on the firm surface of the plate. The trial lasted for 20 seconds and began and ended with an auditory tone. After a minimal inter-trial delay (<10 seconds), the second trial (ie Proprioception condition, Figure 2B) commenced with the participants eyes closed while standing on the firm surface. Following the second trial, trials three (ie Vision condition, Figure 2C) and four (ie Vestibular condition, Figure 2D) were conducted similar to trials one and two. However, for these trials the participants stood on

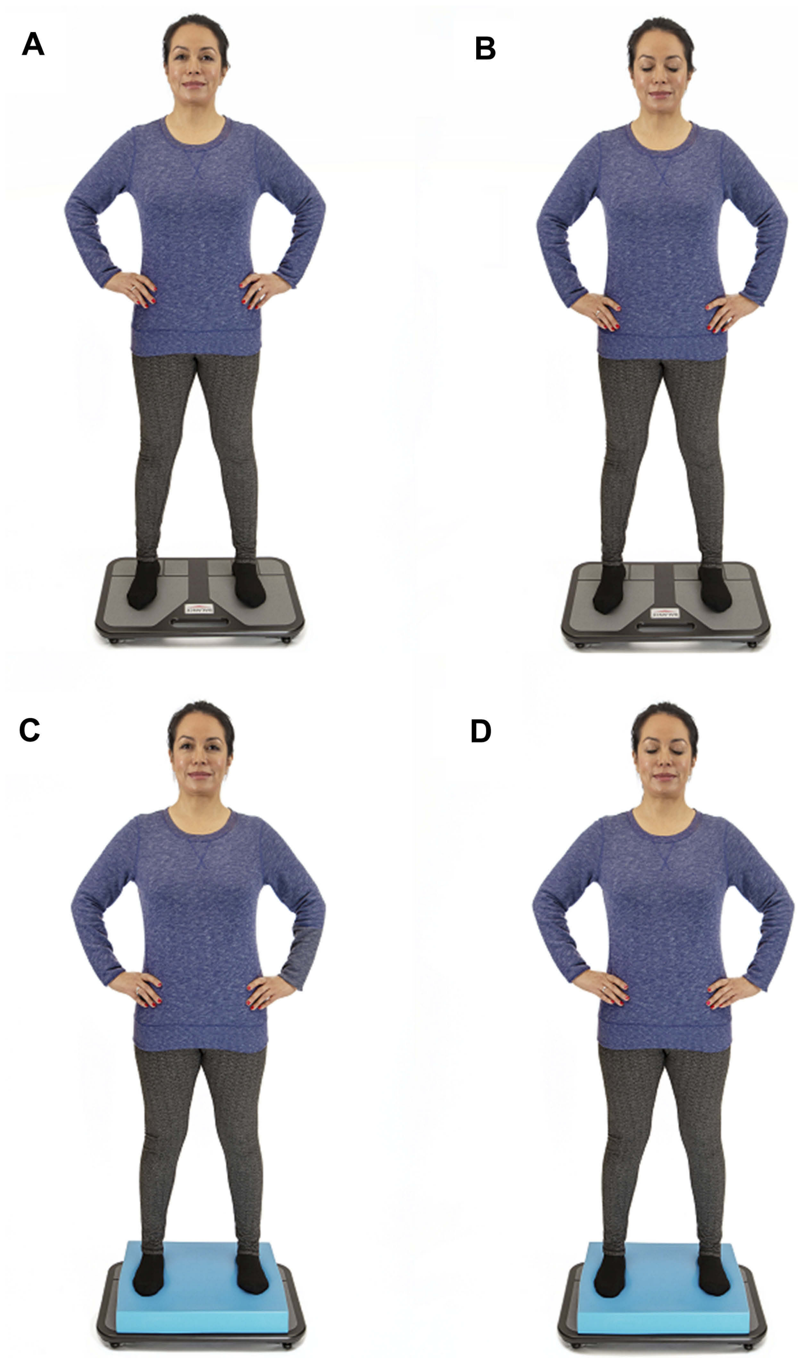

Figure 2 Testing positions for the BTrackS mCTSIB protocol. In all conditions, individuals stood as still as possible on the BTrackS balance plate with feet shoulder width apart and hands on hips. Condition 1 (**A**, Standard) was performed with eyes open while standing on the firm surface of the plate. Condition 2 (**B**, Proprioception) was performed with eyes closed while standing on the firm surface of the plate. Condition 3 (**C**, Vision) and condition 4 (**D**, Proprioception) were performed while standing on foam with eyes open and eyes closed, respectively. Image used with written informed consent of individual shown.
Abbreviations: mCTSIB, modified Clinical Test of Sensory Integration and Balance; BTrackS, Balance Tracking System.

a piece of high-density foam. Specifically, in trial three the participants' eyes were open while standing on the foam, while in trial four, the eyes were closed while standing on the foam. Participants removed their shoes for all testing, however, previous research of similar static balance protocols has found no difference in COP with or without standard footwear.[15]

Data analysis

The result of each BTrackS mCTSIB trial was calculated by the BTrackS Assess Balance software, equivalent to the Total COP Path Length. Total COP Path Length is a proxy for postural sway magnitude whereby larger Total COP Path Length values are indicative of greater postural sway.[9] Total COP Path Length was determined by first quantifying the point to point COP Path Length between successive time points according to the following formula:

$$\text{COP path length} = \left((\text{COP}_{x2} - \text{COP}_{x1})^2 + (\text{COP}_{y2} - \text{COP}_{y1})^2\right)^{0.5}$$

where COP_{x2} and COP_{x1} are adjacent time points in the COP_x (medial/lateral) time series and COP_{y2} and COP_{y1} are adjacent time points in the COP_y (anterior/posterior) time series. The sum of all COP Path Lengths was then added together to get Total COP Path Length. The BTrackS Balance Plate sampling frequency is specified by the manufacturer at 25 Hz for a total of 500 data points in a 20s trial. Only Total COP Path Length was provided by the BTrackS Assess Balance software, thus, no other COP metrics were assessed.

Once all participant tests were completed, BTrackS mCTSIB results were de-identified and assimilated into a single database in preparation for statistical analyses. A quality inspection of the data was performed using a series of rules that determined improper use of the testing protocol, invalid demographics and testing outliers. Less than 1% of the original sample (n=609) profiles was excluded. Following this pre-preprocessing step, the statistical effects of sex (men, women) and testing condition (standard, proprioception, vision, vestibular) on BTrackS mCTSIB, as well as the interaction between sex and condition (sex*condition), was performed using a two-factor analysis of variance (ANOVA) with repeated measures for condition. This analysis was conducted in SPSS (IBM, Armonk, NY) with significance determined at the $p<0.05$ level. Where significant effects were found, Tukey Honest Significant Differences (HSD) were used to determine significant differences between levels of a given factor. Lastly, based on the analyses for sex and condition, percentile rankings were calculated for the 1st, 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90th and 99th percentiles according to the following formula:

$$\text{Percentile ranking} = \text{P}/100\,(\text{N} + 1)$$

In this formula, P represents the percentile rank and N represents the number of mCTSIB results in the distribution of interest.

To quantify the influence of body size on postural sway, body mass index (BMI) was calculated for a large subset of individuals (n=225) according to the following formula:

$$\text{BMI} = \text{Weight}/\text{Height}^2$$

where weight was measured in Kilograms (Kg) and Height was measured in meters (m). For each sex and condition grouping, linear regressions were then performed in SPSS between Total COP Path Length and BMI to obtain R^2 values. R^2 values were between 0 and 1, where 0 indicated no Total COP Path Length variance was explained by BMI (ie no relationship), and 1 indicated all variance was explained by BMI (ie perfect relationship).

Results

Based on the ANOVA, significant differences in Total COP Path Length were found due to sex ($F_{1,602}$=31.3, p<0.001), condition ($F_{4,599}$=1728.8, p<0.001) and a sex*condition interaction ($F_{4,599}$=8.1, p<0.001). These results are visually depicted in Figure 3 and demonstrate that women significantly outperformed men (ie had smaller Total COP Path Lengths) in each of the standard (Tukey HSD, p<0.001), proprioception (Tukey HSD, p<0.001), vision (Tukey HSD, p<0.001) and vestibular conditions (Tukey HSD, p<0.001). Further, the magnitude of sex differences increased across conditions, with the greatest sex difference found in the vestibular condition where both vision and proprioception were compromised.

Analysis of the relationship between body size and BTrackS mCTSIB performance showed that participant BMI explained very little (2% or less) of the variance in Total COP Path Length. Table 1 provides a sex by condition breakdown of these data. In light of these findings, percentile rankings were stratified only by sex and condition, and not body size. These percentile rankings are provided in "look-up" form in Table 2 (women) and Table 3 (men), and serve as a tool for understanding the results of an individual compared to a healthy young adult of the same sex for a given condition. For example,

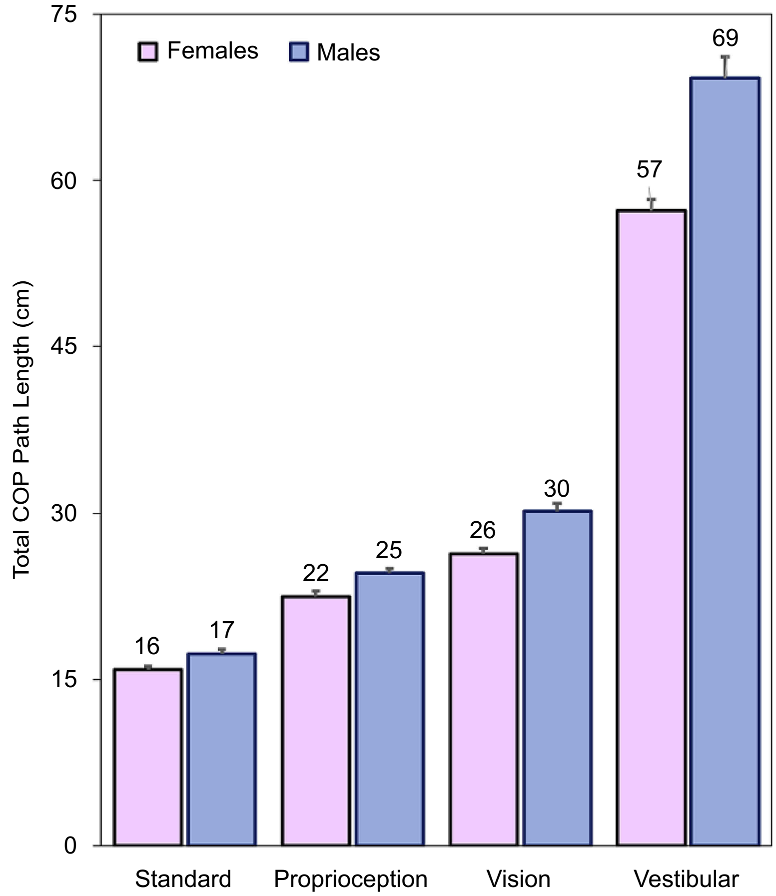

Figure 3 Mean (standard error) Total COP Path Length results for men and women in each BTrackS mCTSIB test condition.
Abbreviations: COP, center of pressure; BTrackS, Balance Tracking System; mCTSIB, modified Clinical Test of Sensory Integration and Balance.

Table 1 BTrackS mCTSIB variance explained by BMI for each test condition

mCTSIB Condition	Males		Females	
	R^2	Variance explained	R^2	Variance explained
Standard (eyes open/firm)	0.001	0.1%	0.020	2.0%
Proprioception (eyes closed/firm)	<0.001	<0.1%	0.008	0.8%
Vision (eyes open/foam)	<0.001	<0.1%	0.008	0.8%
Vestibular (eyes closed/foam)	0.010	1.0%	0.013	1.3%

Abbreviations: BMI, body mass index; BTrackS, Balance Tracking System; mCTSIB, modified Clinical Test of Sensory Integration and Balance.

a man who has a Total COP Path Length of 59 on the vestibular condition is in the 40th percentile. This means his performance is as good as or better than 40% of healthy young adult men.

Discussion

The BTrackS Balance Plate is gaining popularity as an objective, portable and low-cost force plate for balance assessment. In this case, the present study sought to provide an initial set of normative data for the relatively new BTrackS mCTSIB protocol in a large sample of healthy young adults. Differences between women and men were seen across all conditions (ie standard, proprioception, vision, vestibular), with body size having little influence on performance. These findings informed the calculation of relevant percentile rankings for creating "look-up" tables clinicians and research scientists can use in a number of practical ways.

Lower postural sway (ie better balance) in women is a consistent result in the literature across a variety of testing protocols.[11] Since there was very little relationship between body size and Total COP Path Length, the increase in sex differences across the various testing trials

Table 2 BTrackS mCTSIB percentile rankings for women's Total COP Path Length results in each test condition

Percentile	mCTSIB Condition			
	Standard (eyes open/ firm)	**Proprioception (eyes closed/firm)**	**Vision (eyes open/ foam)**	**Vestibular (eyes closed/ foam)**
1st	33	43	44	120
10th	22	31	36	80
20th	19	28	33	70
30th	17	25	30	63
40th	16	23	28	58
50th	15	21	26	54
60th	14	19	24	50
70th	13	18	22	46
80th	12	17	19	41
90th	10	14	16	38
99th	8	9	11	31

Abbreviations: COP, center of pressure; BTrackS, Balance Tracking System; mCTSIB, modified Clinical Test of Sensory Integration and Balance.

Table 3 BTrackS mCTSIB percentile rankings for men's Total COP Path Length results in each test condition

Percentile	mCTSIB Condition			
	Standard (eyes open/ firm)	**Proprioception (eyes closed/firm)**	**Vision (eyes open/ foam)**	**Vestibular (eyes closed/ foam)**
1st	34	53	71	151
10th	26	35	44	97
20th	22	31	36	83
30th	19	28	34	74
40th	17	26	30	69
50th	16	23	28	63
60th	15	21	25	59
70th	14	19	22	54
80th	12	17	21	50
90th	11	15	18	45
99th	9	11	14	31

Abbreviations: COP, center of pressure; BTrackS, Balance Tracking System; mCTSIB, modified Clinical Test of Sensory Integration and Balance.

of the BTrackS mCTSIB suggests that this difference is somehow related to sensory feedback processing and/or difficulty of the testing condition. Specifically, the difference between men and women on the easiest of conditions (ie standard) was minimal when all sources of sensory information were highly available. In contrast, as one or more sources of sensory information were removed/manipulated, women showed a greater resiliency in utilizing the remaining sensory sources to control postural sway.

The present findings are cross-validated by previously published normative data studies for the BTrackS Balance Test (BBT) protocol.[11,16,17] The BBT protocol consists of four trials of static standing with hands on hips and feet shoulder width apart similar to the BTrackS mCTSIB. However, all BBT trials are performed with eyes closed in a manner that is equivalent to the proprioceptive condition (ie trial 2) of the BTrackS mCTSIB. For both the BBT and mCTSIB, young adult women outperformed men and body size had little correlation with performance. Percentile ranking comparisons between the BBT and its corollary (ie trial 2) in the mCTSIB are also highly consistent in magnitude and variance.

The present study was conducted at multiple sites, which may have introduced variability due to environmental factors. That said, the goal of this work is to provide a reference for clinicians and researchers in various field settings. In this case, the additional variance due to the diversity of testing location may actually strengthen the applicability of the results. Further, the present study is limited in that the sample collected may not be representative of the global population at large, as testing sites were primarily located in a single region of a single country (southeast Michigan, USA). Future work will address these limitations by expanding data collection efforts across a larger geographical area.

This study also fails to address known differences in postural sway measured by force plate devices that are seen with age. Work is already underway which will address this need for the clinical and research communities. Lastly, a final limitation of this study is that the decision to evaluate BMI was made post-hoc of balance testing and, thus, it was not possible to retroactively obtain values for all participants. That said, the sample collected was more than adequate for calculating ICC values, given that the recommended standard is at least 30 individuals per group.[18] Indeed, our sample was more than three times greater than that with over 100 men and 100 women per group.

Conclusion

In conclusion, the percentile ranking information provided in this study is an important first step in helping a growing number of clinical and research professionals assess balance more effectively with the BTrackS mCTSIB protocol. Specifically, this information will allow for more adequate comparisons of results with healthy young adults to determine the existence of balance deficits as they pertain to sensory feedback sources. Through this enhanced diagnostic capability, it will be possible to better address the needs of individuals with balance deficits and provide them various balance interventions in a targeted, expeditious fashion.

Acknowledgment

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Disclosure

DJG is eligible for royalties from a pending patent (OMB 0651-0032) related to the technology used in this study. In addition, he has an equity stake (stock options) in Balance Tracking Systems, Inc. This financial conflict of interest is mitigated by a management plan put in place by his academic institution to ensure the integrity of his research. The authors report no other conflicts of interest in this work.

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