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RESEARCH ARTICLE

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Expanded normative data for the balance tracking system modified clinical test of sensory integration and balance protocol

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Abstract

The modified Clinical Test of Sensory Integration and Balance (mCTSIB) is a popular protocol used to assess key sources of sensory feedback utilized during upright standing. The present study aimed to expand the age range of a previous normative sample of only young adult mCTSIB reference data collected using the Balance Tracking System (BTrackS). In total, 1,276 adults between ages 20 and 59 years old completed the BTrackS mCTSIB protocol in this study. The protocol consisted of four, 20-s trials that systematically manipulated the relative contributions of vision, proprioception and vestibular sensory systems. Total Center of Pressure Path Length results showed that females generally outperformed males in all age groups and sensory conditions. Both sexes showed reduced balance with age that started at age 50–59 years in Standard and Proprioception conditions. In the Vestibular condition, both sexes had reduced balance starting at age 30–39 years. In contrast, the pattern of reduction was different between females and males in the Vision condition. In this case, females showed a decline in balance at age 30–39 years compared to 40–49 years in males. These results provide important information demonstrating sensory feedback processing for balance can decline at differential rates based on age and sex characteristics. Percentile ranking look-up tables were also calculated as a practical tool for researchers and clinicians who regularly perform mCTSIB testing.

KEYWORDS

feedback, lifespan, proprioception, sensory, sex, vestibular, vision

1 | INTRODUCTION

Maintaining balance during standing is a fundamental human skill accomplished by minimizing body sway to keep the body's centre of mass over the base of support. Although commonly viewed as a 'motor' act, balance relies on three sensory systems (i.e. proprioception, vision and vestibulation). Ankle position information provided by the proprioceptive system gives sway-related feedback based on an inverted pendulum model of body dynamics (Nashner, Shupert, Horak, & Black, 1989). On the other hand, visual information helps anticipate a loss in balance using head position cues relative to the surrounding environment (Black, Wall, & Nashner, 1983). Lastly, vestibular feedback is needed to monitor and resolve conflicts between head location and the external environment (Nashner, Black, & Wall, 1982).

In light of the above, a number of assessment protocols have been developed to explore the relative contributions of proprioception, vision and vestibulation to balance. The most popular of these methods is the modified Clinical Test of Sensory Integration and Balance (mCTSIB), a derivative of the CTSIB originally developed by Shumway-Cook and Horak (1986). In the mCTSIB, body sway control is measured during various test conditions designed to compromise the availability or reliability of one or more sensory feedback sources. Test manipulations typically include closing one's eyes and/or standing on a compliant foam surface.

Force plate medical devices have been cited as the 'gold standard' for measuring balance, as they provide objective information on body sway via a clinically-relevant metric called Center of Pressure (COP). The Balance Tracking System (BTrackS) is a low-cost, portable force plate with software that supports quick, accurate and reliable mCTSIB testing. Specifically, COP is measured by BTrackS during four static standing trials. The first trial represents the 'Standard' condition, where all three sensory systems are uncompromised (i.e. testing is done with eyes open on a firm surface). The second trial represents the 'Proprioception' condition, where vision is removed by closing the eyes. This manipulation increases reliance on both proprioceptive and vestibular systems but, proprioception is more heavily utilized for balance than vestibular information (Lord, Clark, & Webster, 1991). The third trial represents the 'Vision' condition, where reliability of the proprioceptive system is manipulated by having the individual being tested stand on a foam cushion. In this case, vision is the dominant sense remaining uncompromised over vestibulation (Simoneau, Leibowitz, Ulbrecht, Tyrrell, & Cavanagh, 1992). Lastly, the fourth trial represents the 'Vestibular condition,' where vision is removed (i.e. eyes closed) and proprioception is rendered unreliable with a foam cushion. This situation theoretically causes a shift in reliance to the solely uncompromised vestibular system as the primary source of sensory information.

Recently, an initial set of normative results were reported for the BTrackS mCTSIB protocol based on data from over 600 healthy young adults under the age of 30 years (Goble, Brar, Brown, Marks, & Baweja, 2019). These results provided a critical starting point for clinical assessment, allowing balance dysfunctions to be determined relative to the ideal of a healthy young adult standard. Additionally, development of BTrackS mCTSIB normative data provided a means for assisting both clinicians and researchers in determining the sensory locus of balance impairment through differential diagnosis of sensory systems.

Despite the clear value of previously published BTrackS mCTSIB results, further expansion of this work is necessary. In particular, known balance differences exist based on sex and age, such that less sway is generally seen in females versus males (Goble et al., 2019; Moran, Meek, Allen, & Robinson, 2019) and with older age (Cohen, Heaton, Congdon, & Jenkins, 1996; Peterka & Black, 1990; Whipple, Wolfson, Derby, Singh, & Tobin, 1993). To this extent, the aim of the present study was to provide new sex-based normative data for the BTrackS mCTSIB protocol across the first four decades of the adult lifespan. It was hypothesized that this expansion of previous work would show significant differences in mCTSIB performance with age and that sensory feedback conditions would be differentially impacted in females versus males. This latter finding would be particularly intriguing, providing strong impetus for future studies into the sex-based maturation of balance-related sensory systems.

2 | MATERIALS AND METHODS

2.1 | Participants

There were 1,276 (660 females, 616 males) participants in this study, each of whom self-identified as being healthy and between the ages of 20 and 59 years. Participants gave written, informed consent and self-reported having no known balance impairment at the time of testing. This study was conducted at multiple testing sites that included health fairs, community centres, fitness gyms, religious settings, and educational institutions, among others. Ethical approval for this human subjects-based research was obtained

FIGURE 1 Experimental equipment used in this study included the BTrackS Balance Plate (right) and BTrackS Assess Balance software running on a laptop (left)

from the Institutional Review Board of Oakland University, and all procedures adhered to the Declaration of Helsinki.

2.2 | Experimental equipment and procedures

The equipment for this study is depicted in Figure 1. BTrackS mCTSIB tests were conducted using one of several BTrackS Balance Plates connected to a personal computing laptop running the BTrackS Assess Balance software (Balance Tracking Systems, San Diego, CA). The BTrackS Balance Plate is a US Food and Drug Administration registered force plate medical device that is lightweight (<7 kg) and portable. The force plate measures 0.4 × 0.6 m and has been ecologically validated (Levy, Thralls, & Kviatkovsky, 2018). A converging body of evidence also exists demonstrating the high degree of accuracy and precision associated with the BTrackS Balance Plate for measuring COP data (Goble & Baweja, 2018; O'Connor, Baweja, & Goble, 2016; Richmond, Dames, Goble, & Fling, 2018).

FIGURE 2 The four testing trials utilized in the BTrackS mCTSIB protocol. Each trial requires individuals to stand as still as possible on the BTrackS Balance Plate with feet shoulder width and hands on hips. Trial 1 (a, Standard condition) is performed with eyes open while standing on the firm plate surface. Trial 2 (b, Proprioceptive condition) is performed with eyes closed while standing on the firm plate surface. Trial 3 (c, Vision condition) and trial 4 (d, Vestibular condition) with eyes open and closed, respectively, while standing on a compliant foam cushion

Each testing session was held in an isolated space with limited distractions. The BTrackS Assess Balance software provided an on-screen interface for mCTSIB profile creation, test administration and result interpretation. Due to the user-friendly nature of BTrackS Assess Balance, minimal training was required to learn how to administer the mCTSIB protocol. In this case, test administrators became proficient within several tests performed under the guidance of an experienced user. To start each testing session, the BTrackS Balance Plate was levelled 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 modified Clinical Test of Sensory Integration and Balance or mCTSIB. The mCTSIB 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 mCTSIB results will be based on the Center of Pressure 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 accordance with the instructions, participants stood with feet shoulder width apart on the BTrackS Balance Plate for four consecutive 20-s testing trials (Figure 2). Each trial began and ended with an auditory tone and had the participant place his or her hands on their hips. The first trial (i.e. Standard condition, Figure 2a) required the participant to open their eyes while standing on the firm surface of the plate. After a short inter-trial delay, the second trial (i.e. Proprioception condition, Figure 2b) commenced where participants had their eyes closed while standing on the firm plate's surface. Following trial two, trial three (i.e. Vision condition, Figure 2c) and trial four (i.e. Vestibular condition, Figure 2d) were done in a similar fashion to trials one and two respectively. In this case, however, participants stood on a compliant foam cushion during testing, which was placed on top of the BTrackS Balance Plate. Trial three had the participants' eyes open while standing on the foam, while trial four had the participants' close their eyes while on the foam.

2.3 | Data analysis

Results for each trial (i.e. sensory condition) were calculated and outputted by the BTrackS Assess Balance software. BTrackS mCTSIB results were based on the Total COP Path Length, which is the default metric outputted by the system and a proxy for the magnitude of body sway. 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:

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

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 sampling rate of the BTrackS™ Balance Plate is manufacturer-specified at 25 Hz for a total of 500 data captures in each 20 s trial.

Once all participant testing was complete, BTrackS mCTSIB results were de-identified and assimilated into a single database for statistical analyses. Quality inspection of the data was performed using pre-defined rules that determined improper use of the testing protocol, invalid demographics and/or testing outliers. Less than 1% of the original sample was excluded. The data were then grouped according to sex (i.e. females, males) and age (i.e. 20–29, 30–39, 40–49, 50–59 years).

The statistical main effects and interactions between sex, age and sensory condition (i.e. Standard, Proprioception, Vision, Vestibular) were next determined based on analysis of variance (ANOVA) with repeated measures for condition. ANOVA was conducted in SPSS (IBM, Armonk, NY) with significance determined at the $p < .05$ level. Where significant effects were found, Tukey honest significant differences (HSD) post hoc tests were used to determine

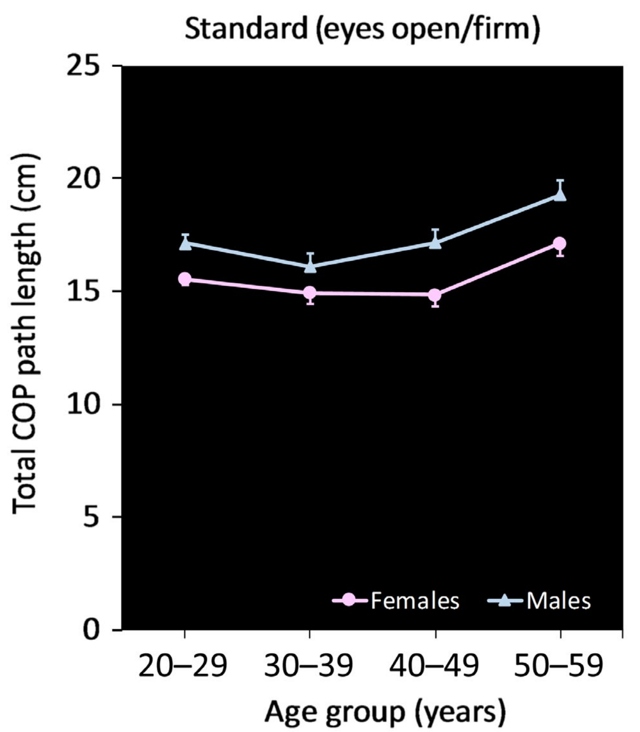

FIGURE 3 Standard condition mean Total COP Path Length for each sex (Females, Males) and age (20–29, 30–39, 40–49, 50–59 years) group. Error bars represent standard error of the mean

significant differences between levels of a given factor. Percentile rankings were also calculated for the 1st, 10th, 20th, 30th, 40th, 50th, 60, 70th, 80th, 90th and 99th percentiles of each age, sex and sensory condition according to the following formula:

$$\text{Percentile Ranking} = \frac{P}{100}(N+1).$$

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

3 | RESULTS

The ANOVA found significant main effects for the factors sex ($F_{1,1,270}$ = 40.2, $p < .001$), age ($F_{3,1,270}$ = 69.0, $p < .001$) and condition ($F_{3,3,810}$ = 4,060.6, $p < .001$). In addition, several interactions were shown to be significant, including sex by condition ($F_{3,3,810}$ = 13.7, $p < .001$), age by condition ($F_{9,3,810}$ = 46.2, $p < .001$) and sex by age by condition ($F_{9,3,810}$ = 1.9, $p < .05$). These results are visualized in Figures 3–6.

With respect to the Standard condition (Figure 3), females had significantly smaller Total COP Path Length than males in all age group categories (Tukey HSD; $p < .05$) except for 30–39 years (Tukey HSD; $p > .05$). Despite this difference, females and males showed a similar pattern of performance across ages. Specifically, Total COP Path Length remained relatively stable across the ages of 20–29, 30–39 and 40–49 years (Tukey HSD; $p > .05$) with a significant increase in Total COP Path Length only found for the 50–59 year age group of both sexes (Tukey HSD; $p < .05$).

In the Proprioception condition (Figure 4), Total COP Path Length was greater across sexes and age groups compared to the Standard

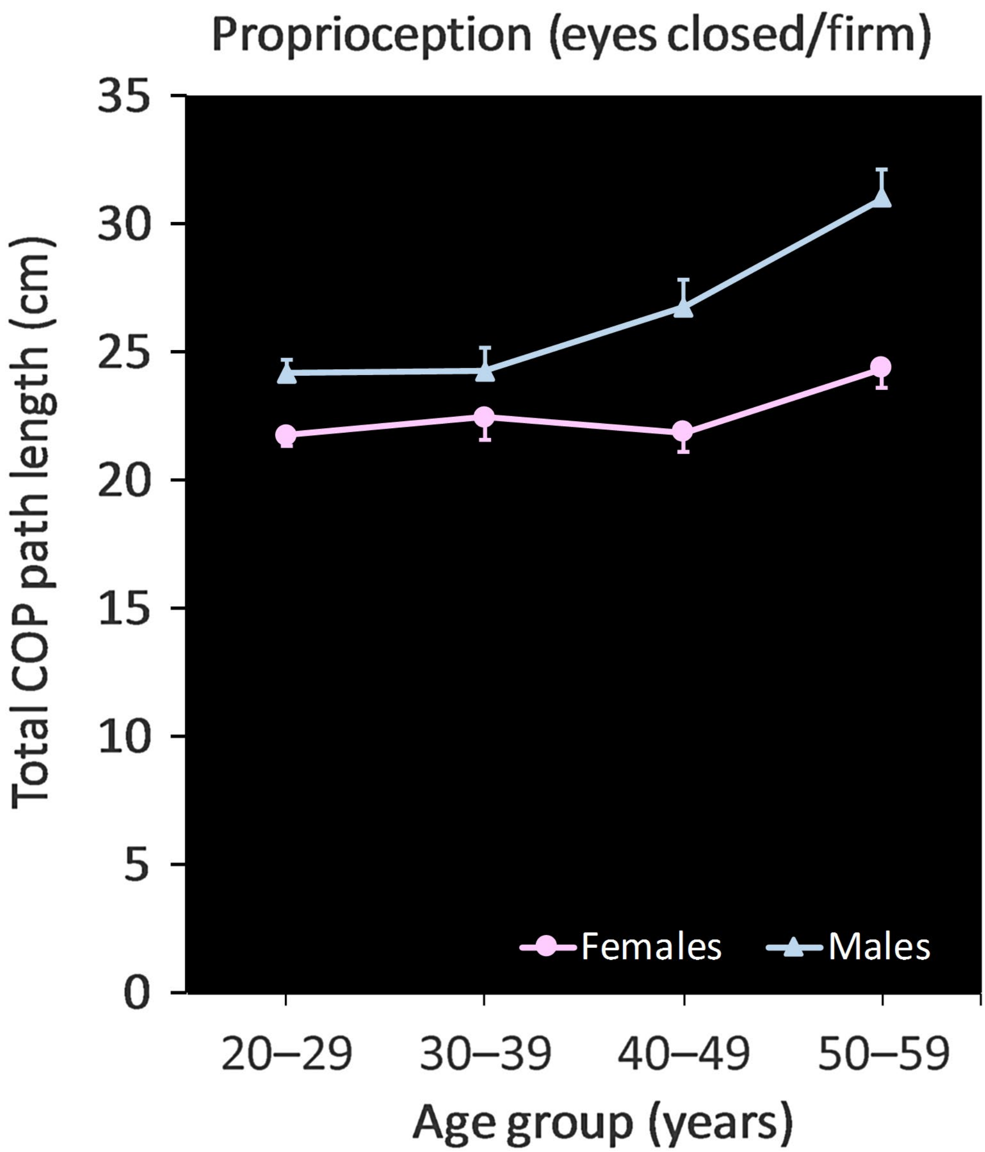

FIGURE 4 Proprioception condition mean Total COP Path Length for each sex (Females, Males) and age (20–29, 30–39, 40–49, 50–59 years) group. Error bars represent standard error of the mean

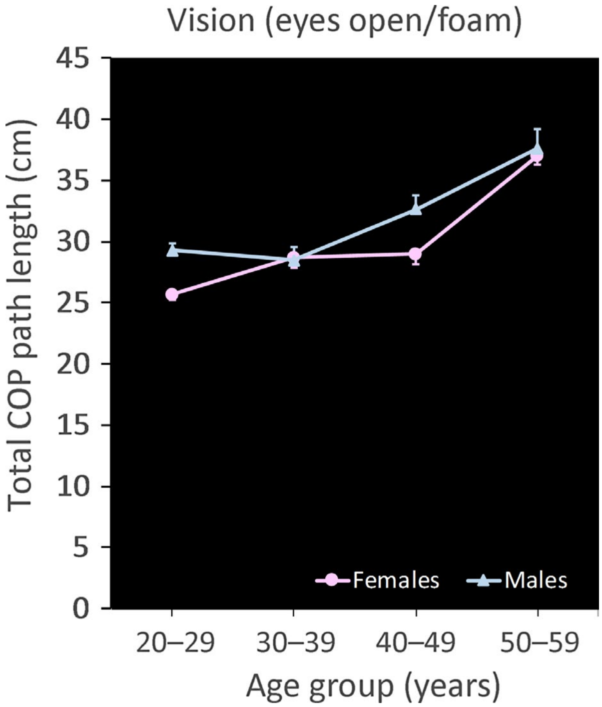

FIGURE 5 Vision condition mean Total COP Path Length for each sex (Females, Males) and age (20–29, 30–39, 40–49, 50–59 years) group. Error bars represent standard error of the mean

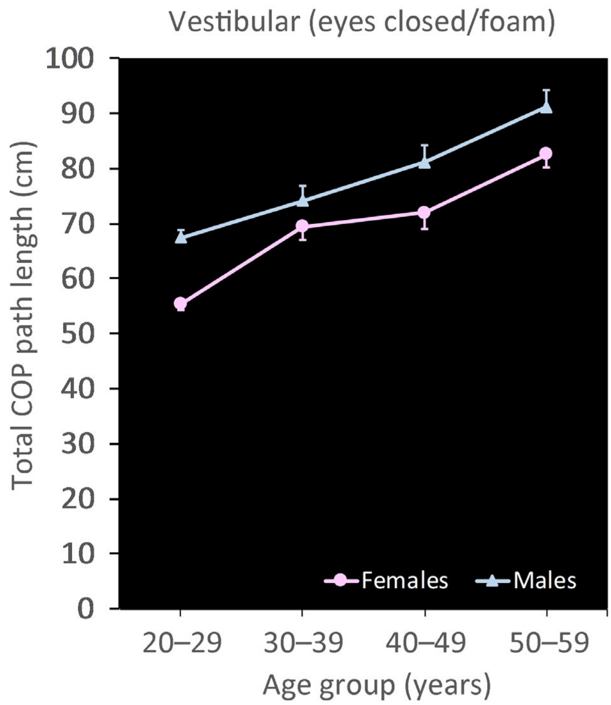

FIGURE 6 Vestibular condition mean Total COP Path Length for each sex (Females, Males) and age (20–29, 30–39, 40–49, 50–59 years) group. Error bars represent standard error of the mean

condition (Tukey HSD; $p < .05$). Females again demonstrated significantly less Total COP Path Length than males across all age groups (Tukey HSD; $p < .05$) except 30–39 years (Tukey HSD; $p > .05$). In this case, it should be noted that females demonstrated a lower mean Total COP Path Length than males. Both sexes showed a significant increase in Total COP Path Length for only the oldest (50–59 year) age group (Tukey HSD; $p < .05$).

Perhaps the most interesting results were found in the Vision condition (Figure 5). Overall, there was a significant increase in Total COP Path Length for the Vision condition compared to the Proprioception condition across sexes and age groups (Tukey HSD; $p < .05$). Similar to other conditions, females performed as well (Tukey HSD; $p > .05$ in 30–39 years and 50–59 years) or significantly better (Tukey HSD; $p < .05$ in 20–29 years and 40–49 years) than males on the Vision condition. However, females and males differed with respect to the effect of age on Vision condition performance. Females had a significant increase in Total COP Path Length from ages 20–29 years to 30–39 years (Tukey HSD; $p < .05$) then maintained balance ability through 40–49 years (Tukey HSD; $p > .05$) before showing another significant increase for 50–59 years (Tukey HSD; $p < .05$). Males, on the other hand, maintained Total COP Path Length at a similar level from ages 20–29 years though 30–39 years (Tukey HSD; $p > .05$), but experienced a significant decline in performance at 40–49 years and 50–59 years (Tukey HSD; $p < .05$).

Total COP Path Length for the Vestibular condition (Figure 6) was significantly greater than the other three conditions (Tukey HSD; $p < .05$). Similar to the Standard and Proprioception conditions, females had significantly lower COP Path Lengths in all age groups (Tukey HSD; $p < .05$) except 30–39 years where they were no different than males (Tukey HSD; $p > .05$). With respect to age, there was a significant decline in balance for both sexes from ages 20–29 years to 30–39 years and again from ages 40–49 years to 50–59 years (Tukey HSD; $p > .05$).

Percentile rankings for men and women in each age group are provided in Tables 1–4. These 'look-up' tables provide a population-based mechanism for comparing future testing results in the context of the sex and age categories utilized in this study. For example, a 53-year-old female who performs the BTrackS mCTSIB, and receives a Total COP Path Length result of 59 on the vestibular condition, would equate to the 80th percentile according to Table 4. This means that her performance is equal to, or better than, 40% of healthy females who are of a similar age.

4 | DISCUSSION

The present study provides an expansion of sex-based normative data for the BTrackS mCTSIB protocol across the first four decades of the adult lifespan. In line with previous studies of the mCTSIB, females generally outperformed males and balance declined for both sexes with age. Interestingly, sex-differences were largely mitigated in the 30–39 year age group for all mCTSIB conditions, and the progression of balance declines with age differed by sex and sensory condition. These results, along with the percentile ranking 'look-up' tables provided, can assist in helping provide more accurate assessments of balance performance for young and middle-aged adults using the BTrackS mCTSIB.

TABLE 1 Total COP Path Length percentile rankings for 20- to 29-year-old females (n = 312) and males (n = 290) in each BTrackS mCTSIB condition

	BTrackS mCTSIB condition							
	Standard (eyes open/firm)		Proprioception (eyes closed/firm)		Vision (eyes open/foam)		Vestibular (eyes closed/foam)	
Percentile ranking	Females	Males	Females	Males	Females	Males	Females	Males
1st	30	36	41	51	44	67	119	151
10th	22	25	31	35	36	42	77	95
20th	19	22	28	31	31	36	66	83
30th	17	19	25	28	29	33	61	74
40th	16	17	22	25	27	30	57	68
50th	15	16	20	22	25	28	53	63
60th	14	14	19	21	23	25	49	59
70th	13	14	17	19	21	22	45	53
80th	11	12	16	16	19	21	41	48
90th	10	11	14	14	16	17	36	43
99th	7	9	9	11	11	13	28	32

TABLE 2 Total COP Path Length percentile rankings for 30- to 39-year-old females (n = 101) and males (n = 104) in each BTrackS mCTSIB condition

	BTrackS mCTSIB condition							
	Standard (eyes open/firm)		Proprioception (eyes closed/firm)		Vision (eyes open/foam)		Vestibular (eyes closed/foam)	
Percentile ranking	Females	Males	Females	Males	Females	Males	Females	Males
1st	27	36	50	51	68	61	140	154
10th	21	21	32	37	39	44	101	109
20th	19	20	28	31	35	35	89	90
30th	17	18	24	27	32	31	75	80
40th	15	16	22	24	30	29	69	75
50th	14	15	21	23	28	26	64	70
60th	13	14	19	20	25	24	61	62
70th	12	13	18	18	23	22	56	59
80th	11	12	16	17	20	20	51	50
90th	10	10	14	14	18	17	42	43
99th	8	8	9	12	15	13	33	35

The observation that females, on the whole, had less Total COP Path Length than males is in line with numerous studies across a variety of balance protocols, including the mCTSIB (Goble et al., 2019; Moran et al., 2019). While it is tempting to ascribe these results to anthropometric differences between males and females, previous research on the BTrackS mCTSIB in young adults showed that participant height and weight characteristic explained less than 2% of Total COP Path Length results (Goble et al., 2019). As an alternative, it could be posited that females have superior balance-related sensory feedback processing abilities compared to males. This hypothesis is supported by a trend in the present data towards increasing sex-differences in the most challenging Vestibular condition, whereby sensory feedback from two key sources of sensory information was manipulated (i.e. Vision and Proprioception).

It has been well established that older adults (age 60+ years) show reductions in balance compared to young adults (Cohen et al., 1996; Goble & Baweja, 2018; Peterka & Black, 1990). However, little is known about changes in balance ability that occur from young adulthood through middle age. From the present findings, it is clear there is an increase in Total COP Path Length (i.e. a balance reduction) that happens even prior to individuals becoming older adults. In Standard and Proprioceptive conditions, where proprioception was not challenged, declines in balance performance were not seen until

TABLE 3 Toal COP Path Length percentile rankings for 40- to 49-year-old females (*n* = 105) and males (*n* = 108) in each BTrackS mCTSIB condition

	BTrackS mCTSIB condition							
	Standard (eyes open/firm)		Proprioception (eyes closed/firm)		Vision (eyes open/foam)		Vestibular (eyes closed/ foam)	
Percentile ranking	Females	Males	Females	Males	Females	Males	Females	Males
1st	30	32	42	56	71	71	141	186
10th	22	25	32	43	45	48	120	129
20th	18	22	29	35	37	42	92	105
30th	17	20	25	32	33	37	78	90
40th	15	18	22	27	27	34	68	77
50th	15	17	20	24	26	31	64	74
60th	13	15	18	22	24	28	59	70
70th	12	13	17	20	22	25	53	62
80th	11	12	15	17	20	23	49	56
90th	8	10	14	15	17	20	43	46
99th	7	8	10	11	15	14	35	37

TABLE 4 Total COP Path Length percentile rankings for 50- to 59-year-old females (*n* = 144) and males (*n* = 114) in each BTrackS mCTSIB condition

	BTrackS mCTSIB condition							
	Standard (eyes open/firm)		Proprioception (eyes closed/firm)		Vision (eyes open/foam)		Vestibular (eyes closed/ foam)	
Percentile ranking	Females	Males	Females	Males	Females	Males	Females	Males
1st	42	41	47	69	78	81	192	197
10th	25	29	36	47	55	59	127	132
20th	22	24	31	39	48	48	102	118
30th	19	21	28	34	42	43	95	104
40th	18	19	26	32	37	36	85	96
50th	16	18	23	30	34	34	77	87
60th	15	17	22	25	31	31	71	76
70th	13	16	20	23	29	29	64	72
80th	12	14	17	21	25	24	59	62
90th	11	12	13	18	21	21	54	54
99th	8	9	10	14	15	14	40	38

age 50–59 years. However, when individuals had proprioception challenged by standing on a compliant foam surface (i.e. Vision and Vestibular conditions), reductions in balance were seen as early as age 30–39 years.

The above results underscore the dominance of proprioceptive feedback over vision and vestibular information in determining balance ability (Lord et al., 1991; Simoneau et al., 1992). Indeed, although many aspects of balance are impacted by age, recent research showed that peripheral proprioceptive loss was a significant predictor of increases in postural sway (Anson et al., 2017). Brain imaging studies have also identified several proprioceptive regions in the ageing brain that significantly predict balance performance in older adults (Goble et al., 2011; Goble, Coxon, Wenderoth, Impe, & Swinnen, 2009). To what extent proprioceptive degeneration is ongoing prior to older adulthood is yet unclear.

This study represents the largest known set of normative mCTSIB data ever accumulated. In order to obtain this large sample, a multi-site approach was necessary, which most likely introduced external variability into the results. That said, a goal of this work was to provide reference data for those using the BTrackS mCTSIB protocol in the clinic and or laboratory setting. Added external variation could, therefore, be a strength of the current findings, as it better reflects differences in testing environments seen in the practical application of the mCTSIB protocol.

It is important to note the various sensory conditions utilized for the BTrackS mCTSIB protocol are not pure measures of proprioception, vision and vestibular information utilization for balance. While closing the eyes might be an effective means of removing visual feedback during standing, use of a foam pad does not achieve the same goal in terms of removing proprioceptive feedback. Indeed, information is still widely available from muscle spindle, joint and cutaneous receptors, although the relationship between these sensory signals and the ground surface is altered. Further, vestibular feedback remains available in all mCTSIB conditions even if lesser utilized.

Future research is planned to widen the BTrackS mCTSIB across the entire adult lifespan and to address paediatric populations. Gathering reliable data from these groups will be challenging, however, given the attentional demands of the mCTSIB protocol and potential safety concerns related to a loss in balance during testing. Attempts will also be made in the future to gather BTrackS mCTSIB data from a wider geographical area. Testing sites in the present study were focused on a single region of a single country (i.e. Southeast Michigan, USA).

BTrackS is an emerging technology for the assessment and training of balance across multiple domains. The results of this study enhance the ability of clinicians and researchers to objectively and accurately determine balance abnormalities in the field or laboratory, respectively. These abnormalities, which have been associated with both poor clinical outcomes and fall risk, can be improved through various exercise-based training interventions. For example, a recent study showed that Total COP Path Length measured with BTrackS can be reduced using a 90-day resistance training intervention called GeriFit (Goble, Hearn, & Baweja, 2017).

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REFERENCES

Anson, E., Bigelow, R. T., Swenor, B., Deshpande, N., Studenski, S., Jeka, J. J., & Agrawal, Y. (2017). Loss of peripheral sensory function explains much of the increase in postural sway in healthy older adults. *Frontiers in Aging Neuroscience*, *9*, 202. https://doi.org/10.3389/fnagi.2017.00202

Black, F. O., Wall, C., & Nashner, L. M. (1983). Effects of visual and support surface orientation references upon postural control in vestibular deficient subjects. *Acta Otolaryngologica*, *95*, 199–201. https://doi.org/10.3109/00016488309130936

Cohen, H., Heaton, L. G., Congdon, S. L., & Jenkins, H. A. (1996). Changes in sensory organization test scores with age. *Age and Ageing*, *25*, 39–44. https://doi.org/10.1093/ageing/25.1.39

Goble, D. J., & Baweja, H. S. (2018). Normative data for the BTrackS balance test of postural sway: Results from 16,357 community-dwelling individuals who were 5 to 100 years old. *Physical Therapy*, *98*, 779–785. https://doi.org/10.1093/ptj/pzy062

Goble, D. J., Brar, H., Brown, E., Marks, C. R. C., & Baweja, H. S. (2019). Normative data for the Balance Tracking System modified Clinical Test of Sensory Integration and Balance protocol. *Medical Devices*, *12*, 183–191.

Goble, D. J., Coxon, J. P., Van Impe, A., Geurts, M., Doumas, M., Wenderoth, N., & Swinnen, S. P. (2011). Brain activity during ankle proprioceptive stimulation predicts balance performance in young and older adults. *Journal of Neuroscience*, *31*, 16344–16352. https://doi.org/10.1523/JNEUROSCI.4159-11.2011

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: Degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and Biobehavioral Reviews*, *33*, 271–278. https://doi.org/10.1016/j.neubiorev.2008.08.012

Goble, D. J., Hearn, M. C., & Baweja, H. S. (2017). Combination of BTrackS and Geri-Fit as a targeted approach for assessing and reducing the postural sway of older adults with high fall risk. *Clinical Interventions in Aging*, *12*, 351–357.

Goble, D. J., Khan, E., Baweja, H. S., & O'Connor, S. M. (2018). A point of application study to determine the accuracy, precision and reliability of a low-cost balance plate for center of pressure measurement. *Journal of Biomechanics*, *71*, 277–280. https://doi.org/10.1016/j.jbiomech.2018.01.040

Levy, S. S., Thralls, K. J., & Kviatkovsky, S. A. (2018). Validity and reliability of a portable balance tracking system, BTrackS, in older adults. *Journal of Geriatric Physical Therapy*, *41*, 102–107. https://doi.org/10.1519/JPT.0000000000000111

Lord, S. R., Clark, R. D., & Webster, I. W. (1991). Postural stability and associated physiological factors in a population of aged persons. *Journal of Gerontology*, *46*, M69–M76. https://doi.org/10.1093/geronj/46.3.M69

Moran, R. N., Meek, J., Allen, J., & Robinson, J. (2019). Sex differences and normative data for the m-CTSIB and sensory integration on baseline concussion assessment in collegiate athletes. *Brain Injury*, *23*, 1–6.

Nashner, L. M., Black, F. O., & Wall, C. (1982). Adaptation to altered support and visual conditions during stance: Patients with vestibular deficits. *Journal of Neuroscience*, *2*, 536–544. https://doi.org/10.1523/JNEUROSCI.02-05-00536.1982

Nashner, L. M., Shupert, C. L., Horak, F. B., & Black, F. O. (1989). Organization of posture control. An analysis of sensory and mechanical constraints. *Progress in Brain Research*, *80*, 411–418.

O'Connor, S. M., Baweja, H. S., & Goble, D. J. (2016). Validating the BTrackS Balance Plate as a low cost alternative for the measurement of sway-induced center of pressure. *Journal of Biomechanics*, *49*, 4142–4145. https://doi.org/10.1016/j.jbiomech.2016.10.020

Peterka, R. J., & Black, F. O. (1990). Age-related changes in human posture control: Sensory organization tests. *Journal of Vestibular Research*, *1*, 73–85.

Richmond, S. B., Dames, K. D., Goble, D. J., & Fling, B. W. (2018). Leveling the playing field: Evaluation of a portable instrument for quantifying balance performance. *Journal of Biomechanics*, *75*, 102–107. https://doi.org/10.1016/j.jbiomech.2018.05.008

Shumway-Cook, A., & Horak, F. B. (1986). Assessing the influence of sensory interaction on balance: Suggestion from the field. *Physical Therapy*, *66*, 1548–1550. https://doi.org/10.1093/ptj/66.10.1548

Simoneau, G. G., Leibowitz, H. W., Ulbrecht, J. S., Tyrrell, R. A., & Cavanagh, P. R. (1992). The effects of visual factors and head orientation on postural steadiness in women 55 to 70 years of age. *Journal of Gerontology*, *47*, M151–M158. https://doi.org/10.1093/geronj/47.5.M151

Whipple, R., Wolfson, L., Derby, C., Singh, D., & Tobin, J. (1993). Altered sensory function and balance in older persons. *Journal of Gerontology*, *48*, 71–76.

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