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An initial set of reference values for the Balance Tracking System (BTrackS) Limits of Stability protocol

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ABSTRACT

Background: The Balance Tracking System (BTrackS) Limits of Stability (LOS) protocol is a relatively new means of evaluating unconstrained dynamic postural control ability. While the reliability of this protocol has previously been established, reference data is currently unavailable to assist in the interpretation of results.
Research Question: What are typical reference values for the BTrackS LOS protocol with respect to sex, height, and BMI?
Methods: A cross= -section of 800 healthy, young adults (aged 18–29 years; 368 men, 432 women) were administered the BTrackS LOS protocol. Sex, height and weight variables were also captured for the participants.
Results: Results of a stepwise linear regression showed that the outcome measure for BTrackS LOS testing (i.e. LOS Area) was larger in taller individuals and in men. Based on these findings, four percentile ranking categories were established and associated look-up tables created.
Significance: The reference values provided by this study offer much needed guidance to clinicians and researchers for the determination of dynamic balance abnormalities based on BTrackS LOS testing.

1. Introduction

Standing upright without falling (i.e. balance) is a fundamental human behavior that relies on the maintenance of postural stability. Postural stability is defined as controlled movement of one's center of mass to keep it within the body's base of support [1,2]. Such control involves interactions among many aspects of the nervous and muscular systems. This includes specialized areas of the brain [3], multiple sensory organs [4], and coordinated motor unit recruitment [5]. To this extent, it is not surprising that postural stability has been cited as a key indicator of health and well-being in humans across the lifespan [6].

A frequently utilized method for evaluating postural stability is the quantification of center of pressure (COP) location from the foot forces sensed by a gold standard force plate during standing. COP location is a proxy for center of gravity and, thus, changes in this measure during standing reflect postural stability. Interestingly, most force plate postural control protocols implement static testing procedures, instructing the participant to "stand as still as possible". This approach, while advantageous for safety and ease of administration, fails to provide important information regarding dynamic scenarios, where COP location must actively be repositioned [7]. Indeed, previous research has demonstrated that greater dynamic postural stability correlates with enhanced agility in athletes [8], improved functional performance in older adults [9], and improved outcomes for clinical populations [10,11].

The most common methodology for measuring dynamic balance is the Limits of Stability (LOS) protocol implemented using a force plate device. This test uses biofeedback of COP location to guide shifts in participant's center of mass towards the boundaries of their base of support. Traditionally, LOS testing has involved COP displacements towards eight target directions (i.e. Front, Back, Left, Right, Front Left, Front Right, Back Left, Back Right) set at the theoretical limits of biomechanical ankle motion, based on height. This approach, while reliable [6,12–15], neglects the inherent anthropometric variability within testing populations and, thus, constrains true performance capabilities.

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The Balance Tracking System (BTrackS) is a low-cost, portable force plate with multiple standardized testing protocols for postural stability assessment. To improve traditional, target-based LOS paradigms, an alternative LOS protocol was recently developed for BTrackS. Rather than rely on sub-optimally placed targets to guide COP movements towards the base of support boundaries, the BTrackS LOS test provides an opportunity to self-determine limits in all directions through volitional COP displacement. This is achieved via onscreen biofeedback of the current COP location overlaid on an image of the BTrackS Balance Plate, and an overlay of the maximum LOS Area achieved based on the furthest displacement of COP from the plate center in all directions. In this case, participants with larger LOS Areas are assumed to have a larger functional bases of support and greater dynamic postural stability.

A previous study has already established that the BTrackS LOS protocol is reliable across multiple testing instances [16]. An important next step to enhance the efficacy of this protocol is to define a set of healthy reference data as points of comparison for individual results, as has been done previously for a number of other BTrackS protocols [17–21]. When assessing dynamic postural stability in clinical, field or research situations it is vital to have reference data to help interpret the relative normality of participant performance. Additionally, reference data is valuable for establishing the presence of dynamic postural control dysfunction and/or meaningful changes in performance over time due to various balance interventions.

Therefore, the present study sought to generate the first known reference dataset for the BTrackS LOS protocol. This was accomplished by testing a large sample (n = 800) of healthy young adults and determining percentile ranking look-up tables. The relationship between sex, height, and body mass index (BMI) with BTrackS LOS was explored, given previous results from the traditional, targeted LOS approach [6,22–24]. It was expected that men would outperform women and taller versus shorter individuals would have larger LOS Areas. Such results provide much needed comparator data to guide the determination of dynamic balance dysfunction, and/or assist with performance evaluation over time.

2. Methods

2.1. Participants

Data for this study were obtained from 800 healthy young adults between the ages of 18 and 29 years. This sample consisted of 432 women (average±SD Age=20.7 ± 2.0 yrs, Height=165.7 ± 6.8 cm, BMI=23.6 ± 4.2 kg/m^2) and 368 men (average±SD Age=21.4 ± 2.4 yrs, Height=180.5 ± 7.4 cm, BMI=25.6 ± 4.3 kg/m^2). Participants had to self-report being in good general health at the time of testing and no known balance impairments over the previous six months. To enhance sample diversity, testing was performed at multiple sites in five geographical locations (Michigan, Colorado, Northern Ireland, Mississippi, Indiana). This included academic settings, in-home testing, fitness centers, community events, and others. Ethical approval for all protocols was obtained from the relevant local Institutional Review Board entities and research procedures conformed with the Declaration of Helsinki. Written, informed consent was required from participants prior to undertaking the study.

2.2. Experimental materials

The primary equipment used for this study was the BTrackS Assess Balance system (Balance Tracking Systems, San Diego, CA, USA). This system is shown in Fig. 1 and consists of the BTrackS Balance Plate and a Windows-based computer running the BTrackS Assess Balance software application. The BTrackS Balance Plate is a patented (US Patent 10,660,558, 2020), light weight (<15Kg) force plate, with a 40 cm x 60 cm standing surface. The plate's validity and reliability for COP measurement has previously been established on multiple occasions [25–27]. The BTrackS Assess Balance software provided a user-friendly interface for profile creation, test administration and result interpretation.

Fig. 1. The Balance Tracking System (BTrackS) Balance Plate connected via Universal Serial Bus (USB) to a laptop computer running the Assess Balance software.

2.3. Experimental protocol and procedures

Prior to balance testing, participants self-reported their birth-assigned sex (i.e. male or female), as well as their current height and weight [28]. Where necessary, non-SI unit height measures were converted to cm, and weights to kg. These two variables were then used to calculate the participant's BMI according to the following formula:

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

BMI was utilized rather than weight, as it provides a better indication of body mass distribution and obesity [29].

Participants were subsequently administered the BTrackS LOS protocol in a quiet, distraction-free environment. A depiction of the test is shown in Fig. 2, where participants stood with feet shoulder width apart and centered on the BTrackS Balance Plate. Centered referred to a standardized position on the plate that was defined as having the medial malleoli of the left and right feet along the horizontal gridline of the plate and feet equal distance from the plate's midline. Participants were not allowed to wear shoes, and were free to use their arms as they saw fit. A computer screen displaying the BTrackS LOS test interface was located to the front of the participant, where it could be easily viewed during testing. For the test, participants were instructed to lean as far as they could in all directions while keeping the bottom of their feet completely on the surface of the plate.

Onscreen biofeedback was given to participants during testing in the form of a yellow dot representing their real-time COP location overlaid on an image of the BTrackS Balance Plate. As the participant leaned and displaced their COP location to a new maximum from the plate's center, separate biofeedback was given in the form of a blue area over the image of the plate on the screen. This area, known as the overall LOS Area, was also updated in real time with the real-world size of the blue area created in cm^2. No time constraint placed on participants, rather they were instructed to increase the total blue area until they felt it was no longer possible. At that point in time, the tester selected the "End" button to terminate the test. The duration of BTrackS LOS testing was less than two minutes for most participants.

2.4. Data analysis

LOS Area determined by the BTrackS Assess Balance software was

Fig. 2. Example of an individual performing BTrackS LOS testing (left side) and an enlarged view of the testing screen (right side) with biofeedback of the current COP location and overall LOS area created.

used as the primary dependent variable for this study. Normality of this measure was confirmed based on inspection of histograms and a sample size that greatly exceeded the n = 30 standard of the Central Limit Theorem [30]. Predictors of LOS Area were quantified based on a forward, stepwise linear regression of the sex, height and BMI. At each step of the regression, variables were selected based on *p*-values, with a threshold of $p < 0.05$ used for inclusion in the final model. This analysis was performed in IBM SPSS Statistics (version 28, IBM Corp., Armonk, NY, USA).

Following the establishment of significant LOS Area predictors, categories for percentile rankings were created. Ranking values were calculated for the 1st,10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, 90, and 99th percentiles according to the following formula:

Percentile Ranking = P/100 (N+1)

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

3. Results

Two significant predictors of LOS Area were identified by the stepwise regression (F_{2799} =206.7, $p < 0.001$). The largest predictor was height of the individual ($t = 7.1$, $p < 0.001$), whereby taller individuals were significantly more likely to have a larger LOS Area (Fig. 3). The second predictor was the sex of the individual, such that men had a significantly larger LOS Area ($t = 4.2$, $p < 0.001$) than women, independent of height (Fig. 4). Based on these results, percentile rankings were calculated separately for men and women and stratified by two different height categories (Shorter and Taller). The Shorter category included all individuals of a particular sex who were average height or shorter (Men≤180 cm; Women≤165 cm). The Taller category included all individuals taller than average height (Men≥181 cm; Women≥166 cm). A look-up table of percentile rankings for each sex/height

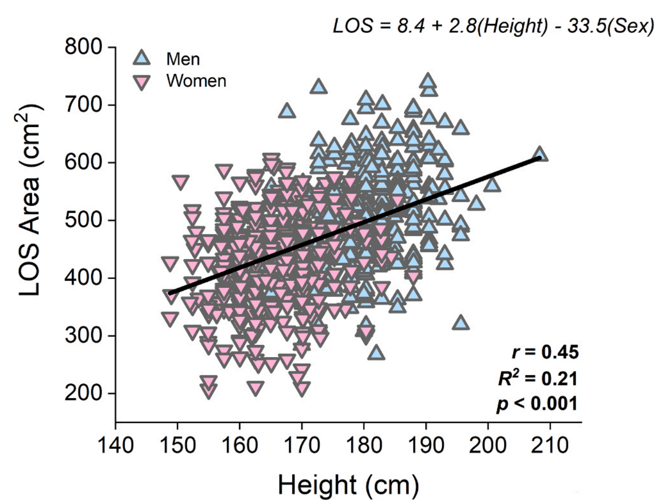

Fig. 3. Scatterplot demonstrating the significant relationship between Height and LOS Area across men and women along with the associated regression equation.

category is provided in Table 1, as well as sample size, average and standard deviation metrics.

4. Discussion

The aim of the present study was to develop an initial set of BTrackS LOS reference values using a large sample (n = 800) of healthy, young adults. Based on stepwise linear regression, two factors (i.e. height and sex) were found that significantly influenced participant performance. Specifically, taller individuals and men demonstrated larger LOS Areas than shorter participants and women. BMI (i.e. obesity status) was not a

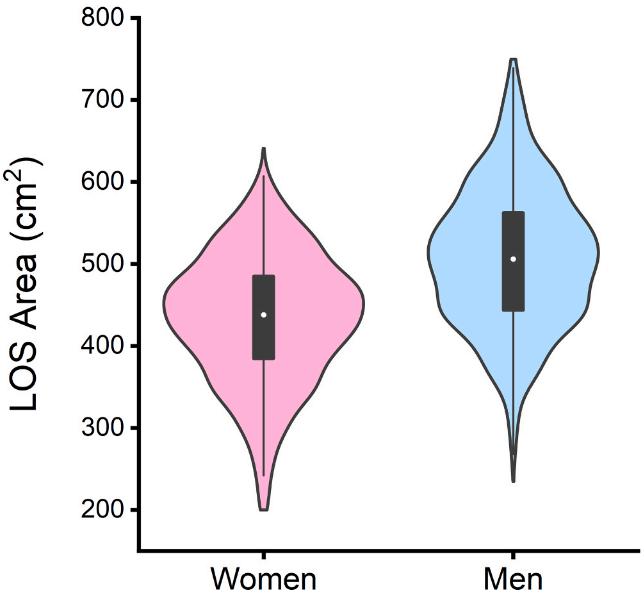

Fig. 4. Violin plots demonstrating the significantly greater LOS Areas demonstrated by men versus women participants.

Table 1
Percentile ranking look-up table for shorter/taller men and women in this study.

	Men		Women	
	Shorter (≤180 cm)	Taller (≥181 cm)	Shorter (≤165 cm)	Taller (≥166 cm)
99th	694	709	586	583
90th	605	638	516	539
80th	556	602	485	521
70th	534	569	463	486
60th	510	553	445	471
50th	484	522	425	453
40th	462	505	403	435
30th	440	487	378	420
20th	418	455	352	388
10th	382	428	322	347
1st	316	339	229	243
N	203	165	225	207
Average	490	529	420	448
Standard Deviation	82	83	78	75

significant predictor of BTrackS LOS performance in the regression model. These results were used to inform the creation of four percentile ranking look-up tables (Shorter Men, Taller Men, Shorter Women, Taller Women) that can serve as much needed comparative results for balance testing practitioners.

While studies of static postural stability have shown little to no evidence that height influences performance [17,19,20], the present, dynamic balance study indicated that taller versus shorter individuals had significantly larger LOS Areas. This finding aligns with the results from several dynamic balance studies using a targeted LOS approach [22–24] and may best be explained by biomechanical factors. Specifically, taller individuals have larger feet than shorter individuals and, thus, have a larger base of support within which to create their LOS Area [31]. Additionally, taller individuals have longer lever arms when rotating their body about the ankle joint. In this case, equivalent angular ankle displacements between two individuals of the different heights will result in greater linear displacements of the center of mass, and COP, for taller versus shorter individuals [32].

Beyond the variance explained by participant height, sex was also a significant predictor of BTrackS LOS performance in this study. Specifically, men demonstrated larger LOS Areas than women independent of the overall differences in height between the two sexes. This finding is particularly intriguing, as it contrasts the results of static balance studies based on standardized BTrackS protocols in large samples (n > 1000) of healthy individuals [17–21]. Such studies have consistently shown that women have superior performance to men on tests of static balance, even when asked to undergo trials of varying complexity (i.e. eyes open/closed or with/without standing on a foam cushion).

The mechanisms underlying such sex-related differences in static and dynamic balance performance remain unclear. Indeed, large-scale BTrackS studies have previously failed to show anthropometric differences between men and women substantially impact static balance performance [17,19,20], while a possible explanation based on greater tactile sensitivity in women's feet has been put forward [33]. In the case of dynamic balance, especially as it pertains to the BTrackS LOS protocol, strength differences between men and women could play an important role, but this hypothesis remains untested. Fundamentally, men have been shown to have greater relative ankle strength than women [34], which would be advantageous for generating and maintaining the larger ankle torques associated with boundary-driven COP displacements during the BTrackS LOS task.

Body size and obesity status, as measured by BMI, did not explain a significant amount of BTrackS LOS Area variance for the individuals in this study. While greater BMI has previously been correlated with lower performance on some target-based LOS outcomes from children [23], previous work with adults has failed to show a relationship between BMI and traditional LOS test performance [6,22]. These findings, taken together, suggest that there may be a developmental difference in dynamic balance as it pertains to body size and obesity status. In this case, future studies are warranted to determine which developmental adaptations to BMI status might occur to overcome the impact obesity has on dynamic balance.

The reference data in this study is a crucial first step to enhancing the understanding and use of BTrackS LOS results by practitioners in many clinical, field and research settings. That said, the reported results remain limited on several fronts. First, the data gathered here were from a narrow spectrum of healthy adults ranging in age from 18 to 29 years. While this sample has value in that it provides a comparison to the best-case scenario of BTrackS LOS performance, it remains necessary to define reference data for other age groups, such as children and older adults. Second, the present study was conducted across multiple sites in five geographical locations. This approach likely introduced variability in results due to environmental factors, multiple testers and testing sites. That said, the BTrackS LOS protocol is commercially available and utilized worldwide. Since the goal of this work is to provide reference values for clinicians and researchers currently using this protocol throughout the world, additional variance due to the diversity of testing location may actually strengthen the results widespread applicability.

In conclusion, it is hoped that the present research findings can enhance the ability of practitioners to objectively and accurately determine dynamic balance abnormalities based on the results of BTrackS LOS testing. Such abnormalities have been associated with poorer clinical outcomes and fall risk and may be improved through exercise-based training interventions. To this point, a recent study showed that LOS Area can be improved and maintained with just 3-min of training, five days a week for six weeks, using the BTrackS Target Tracking Training protocol [35]. Future work in this direction, will no doubt benefit from also considering shifts in the percentile rankings of the participants tested using the results provided in the present study.

Conflict of interest statement

DJG is eligible for royalties from a patent (US Patent 10,660,558, 2020) 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 other authors of this manuscript report no conflicts of interest in this work.

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