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Comparison of simultaneous static standing balance data on a pressure mat and force plate in typical children and in children with cerebral palsy

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ABSTRACT

Background: Balance testing is an important component in treatment planning and outcome assessment for children with Cerebral Palsy (CP). Objective measurement for static standing balance is typically conducted in motion labs utilizing force plates; however, a plantar pressure mat may prove to be a viable alternative for this type of balance assessment.
Methods: This study examined static standing balance simultaneously on a force plate and a plantar pressure mat in 30 typically developing (TD) and 30 children with CP to determine if valid measures of static standing balance could be obtained in children with CP using a pressure mat.
Results: Examination of the data provided evidence that reliable and valid measures of static standing balance can be produced with a plantar pressure mat for both groups. Five variables out of the 21 variables examined were found to be reliable and valid on both devices (pressure mat and force plate) for both subgroups (TD and CP). The variables medial/lateral (ML) average radial displacement, range moved-ML, anterior/posterior average velocity, ellipse area, and area per second were found to have high test-retest reliability (ICC > .6) and possess discriminant validity between the subgroups (TD vs. CP). Additionally, the ellipse area and area per second variables also had the ability to discriminate between GMFCS levels. A normative center of pressure (CoP) balance data set using all 21 variables was also established for typically developing children for both devices (pressure mat and force plate) within this study.
Significance: The ability to utilize a portable plantar pressure mat for quick and reliable standing balance measurement allows for expanded ability to capture objective data in a variety of settings thereby increasing opportunity for outcomes analysis.

1. Introduction

Cerebral Palsy (CP) is a neurologic condition frequently encountered by pediatric physical therapists [1]. CP is caused by injury to the brain that can occur before, during, or shortly after birth which produces motor impairments and possible sensory deficits [1,2]. Long term effects of this brain lesion may include: abnormal muscle tone, impaired voluntary muscle control, increased muscle tightness, muscle weakness, and impairments of the sensory, visual, and cognitive systems. These deficits impair balance and affect ambulation in the child with CP; limiting the ability to function at the same physical level as their peers [3–9].

Many ambulatory children with CP benefit from orthopedic intervention to improve standing, balance, and walking abilities. These orthopedic interventions can range from stretching, botulinum toxin injections, orthoses, and surgical interventions [10–12]. Physical therapists utilize balance training to improve walking function in children with CP [4]. Clinical observations suggest that these interventions result in improved balance; however, there are no simple methods available to obtain quantitative balance data to support those clinical perceptions. Advancing quantifiable balance data collection techniques will aid the clinician's understanding of balance and

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stability in stance (the first prerequisite to walking) in children with CP, thereby improving treatment planning and outcome assessment [13].

Motion analysis laboratories (MALs) typically consider the use of force plates as the gold standard for measuring static standing balance; however, a more cost effective and portable tool for measuring balance is the plantar pressure mat [14,15]. For this study a Tekscan HR Mat system (Tekscan Inc., South Boston, MA), consisting of a thin plantar pressure floor mat and lap top computer, was utilized to measure static standing balance. Raw data produced by the HR mat were exported into Matlab and entered into a series of equations to produce 21 Center of Pressure (CoP) measures that were compared to the same 21 measures of balance produced by raw data exported into Matlab from simultaneous data collection using an AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA).

The aims of this study are multifold. The first is to compare the test-retest reliability and validity of static standing balance measures obtained from the pressure mat in typically developing (TD) and children with CP versus simultaneous data collection on a force plate. The second is to assess the discriminatory abilities between typically developing children and children with CP with each device. The third is to define available balance testing variables, as well as to provide a typically developing data set for comparisons. The final aim is to produce a method of balance assessment that is portable and comparable to the gold standard of static standing balance testing.

2. Methods

After obtaining local institutional review board approval, a prospective study of 60 participants was conducted in a pediatric MAL for children with spastic diplegic or hemiplegic CP (n = 30) as well as typically developing children (n = 30). Participants ranged in age from 7 through 18 years with a mean of 12 years in both groups. Among the children with CP, 16 had spastic diplegia and 14 had hemiplegia (8-right; 6-left) with 17 functioning at a Gross Motor Function Classification System (GMFCS) Level I and 13 at Level II.

Balance data were collected simultaneously on a Tekscan HR Pressure Mat and on a single AMTI force plate. The pressure mat was laid directly on top of the embedded force plate and data were collected at 120 Hertz (Hz) for 30 second on both instruments. Calibration was performed on both the mat and force plate as per the manufacturer's specifications prior to initiation of each subject's data collection. The force plate amplifier was zeroed with the pressure mat on top. Subjects were instructed to stand still on both feet with hands comfortably at their sides and eyes open, looking straight ahead at a static target for 30 second while data were collected. Trials were collected consecutively until three successful trials were obtained. Subjects stepped off and then back on the mat and force plate combination after each trial. If the subject moved during data collection (e.g. distracted by a noise with resultant head turn), that trial was deemed unsuccessful and another trial was collected.

The raw unfiltered force plate data were exported from Vicon as a C3D (Coordinate 3-Dimensional) file, which was then exported to ASCII as a CSV (comma separated variable) file using Motion Lab System's C3D Editor (Motion Lab Systems, Inc., Baton Rouge, LA). This data file was uploaded into Matlab 2009b and CoP X & Y coordinates were computed. The Tekscan data (X, Y coordinates of the CoP) were exported from Tekscan as a CSV file and uploaded into the same Matlab program. A second order, 10 Hz Butterworth low pass filter was run for all CoP data points. Once uploaded and filtered in Matlab, the CoP X & Y coordinate data were processed through a series of equations.

Variables were defined and computed in Matlab as follows (See Appendix A for equations and units of measure).

- **Sway Path Length (SPL)** refers to the length of the path taken by the CoP data points as if one could stretch them out into a single line and measure the length of that line (Fig. 1) [16].
- **Range Moved (Range)** is defined as the distance moved by the CoP data points in a particular direction. [16] Range Moved in the medial-lateral (ML) direction **(Range-ML)** refers to the distance moved by, or maximal excursion of, the CoP data points in the medial and lateral, or X, direction. Range Moved in the anterior-posterior (AP) direction **(Range-AP)** refers to the distance moved by, or maximal excursion of, the CoP data points in the anterior-posterior, or Y, direction (Fig. 2) [16].
- **Average Radial Displacement (aRadial)** is how far a subject varies from the CoP centroid, on average. It can be examined overall **(aRadial-OA)**, or isolated to the AP **(aRadial-AP)** or ML **(aRadial-ML)** direction. The absolute value is used to remove any negative values for the averages (Fig. 3) [17].
- **Average Velocity Overall (aVel-OA)** is defined as the distance moved in the sway path length divided by the total time of assessment [17]. Average Velocity in the medial-lateral direction **(aVel-ML)** refers to the average velocity by which a subject goes from one CoP data point to another in the medial-lateral, or X, direction. Average Velocity in the anterior-posterior direction (**aVel-AP)** refers to the average velocity by which a subject goes from one CoP data point to another in the anterior-posterior, or Y, direction [17].
- **Average Acceleration (aAcc)** is related to average velocity and measures the degree a subject accelerates or decelerates (i.e. changes in velocity) from one CoP point to the next, and then averages these points. The absolute value is used so that decelerations do not cancel accelerations. Average Acceleration Overall **(aAcc-OA)** refers to the average acceleration of the CoP data points in both the X and Y direction [18]. Average Acceleration in the medial-lateral, or X, direction is referred to as Average Acceleration ML **(aAcc-ML)** with average acceleration in the anterior-posterior, or Y, direction referred to as Average Acceleration AP **(aAcc-AP)** [18].
- **Average Jerk (aJerk)** is related to average acceleration, and it measures the degree a subject makes changes in acceleration by moving from one CoP point to the next, with averaging of these points. Jerk is a second derivative of velocity while Acceleration is a first derivative of velocity. Average Jerk was calculated in 3 forms: ML **(aJerk-ML),** AP **(aJerk-AP)** and overall **(aJerk-OA)**.
- **Area per Second (sArea)** measures the area of a triangle formed by two consecutive CoP XY data points and the CoP centroid. For each consecutive pair of CoP points (along with the centroid), there will be another triangle. Each of these triangles has an area. The farther away the subject is from the center, the larger the area will be. Also, the faster the subject is swaying, the larger the area. Since the Area per Second is an average of the areas made by these triangles over time (per second), it is therefore influenced by both the speed a subject moves from one CoP data point to another as well as the distance between these points (Fig. 4).
- **Circle area (cArea)** refers to the circular area created by the tracing of the CoP data points [16]. It is a 95% Confidence Interval (CI) that contains approximately 95% of the CoP data points (Fig. 5).
- **Ellipse Area (eArea)** refers to the elliptical area created by the tracing of the CoP data points [16]. It is a 95% CI that contains approximately 95% of the CoP data points. The ellipse is rotated to maximize the area it eclipses. The ellipse major (a) and minor (b) axes are derived, each multiplied by a 95% F-value, and then the area = πab equation for an ellipse is applied [16].
- **Ellipse Angle (eAngle)** is the angle of the major axis of the Ellipse Area on the Y (A/P) axis. If the ellipse is directly on the Y (AP) axis, this angle will be zero. If the ellipse is tilted toward the left toes, this angle will be negative. If the ellipse is tilted toward the right toes, this angle will be positive. It should be noted that these degrees + or – are reversed from a typical counter-clockwise coordinate system (Fig. 5) [19].
- **Frequency Revolve (rFreq)** is a measure of how rapidly the subject orbits the CoP centroid. It accounts for changes in direction, and,

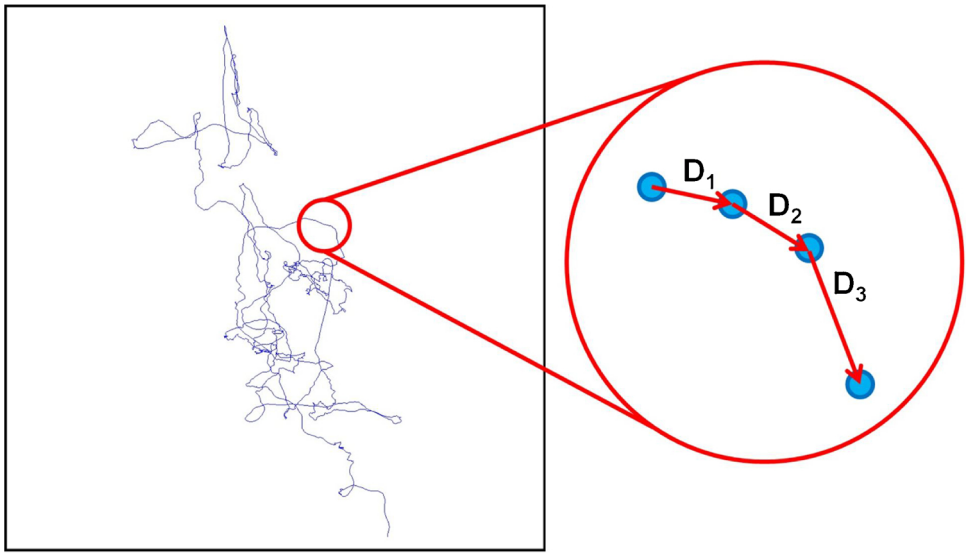

Fig. 1. Sway Path Length (SPL): the length of the path taken by the CoP data points, as seen on the left with a zoomed in view on the right.

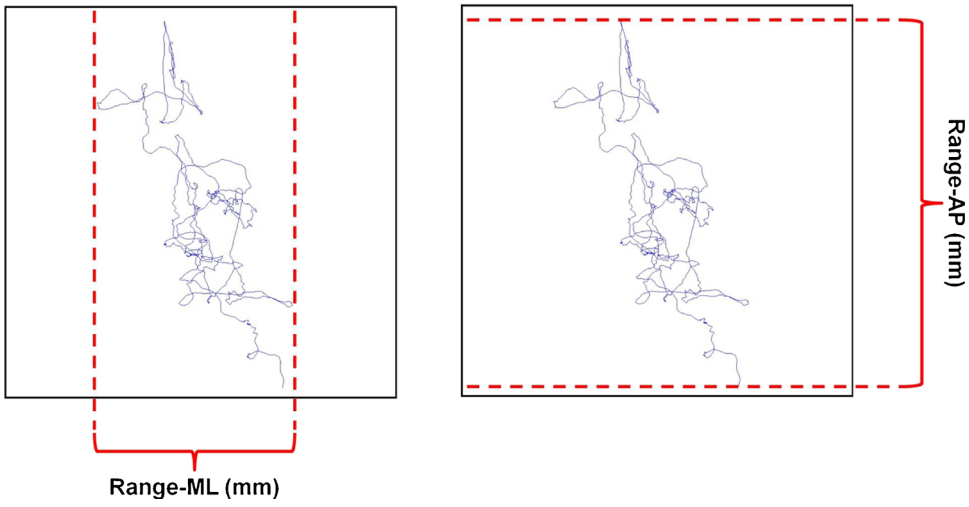

Fig. 2. Range Moved (Range): represents the maximal distance moved by the CoP data points in each direction. Reported in M/L & A/P directions.

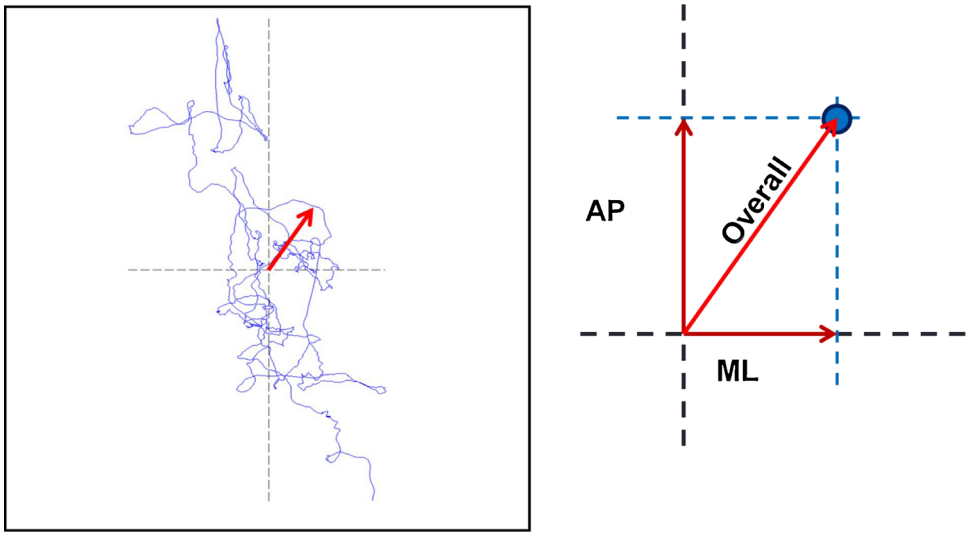

Fig. 3. Average Radial Displacement (aRadial): the distance a subject varies from the CoP centroid, on average. This measure is reported in overall distance, isolated ML and isolated AP directions.

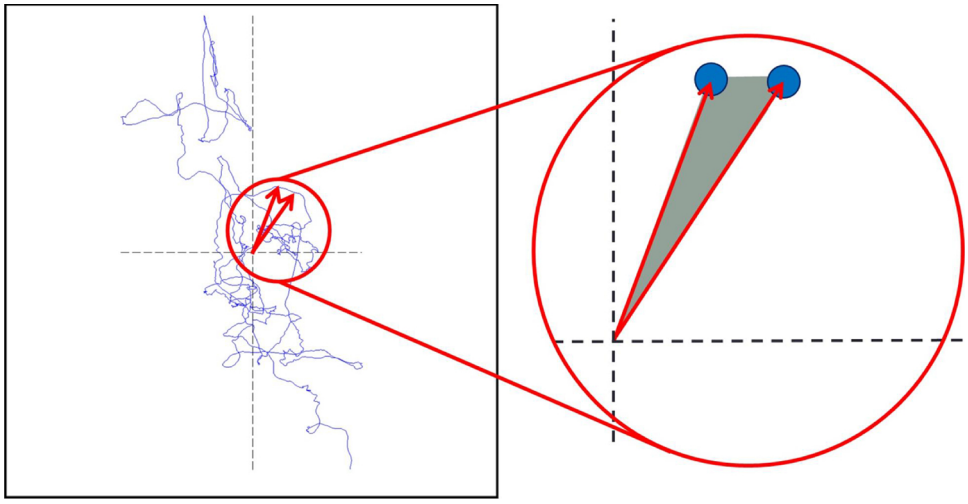

Fig. 4. Area per Second (sArea): measures the area of a triangle formed by two consecutive CoP XY data points and the CoP centroid. sArea is an average of these triangular areas over time, and therefore influenced by both the speed of a subject as well as the distance moved.

therefore, it is not necessary for a subject to always orbit in the same direction or go completely around. As an example, a Frequency Revolve of 0.333 would suggest that the subject revolves about 1/3rd of the way around each second.

- **Median Vibration Frequency (mFreq)** refers to the middle or median frequency of the various vibration frequencies observed in the sway path length of the CoP [17]. It is derived from a Hann Filter and then a Fast Fourier Transform.

3. Statistical analysis

Statistical analysis was performed with either Microsoft Excel 2010 (Redmond, WA) or IBM SPSS 21.0 for Windows (Armonk, NY). Statistical significance was set at alpha = .05 with a 95% confidence interval. The data were reviewed and checked for appropriate parametric assumptions. Descriptive statistics were generated for the entire group as well as by subject type (CP vs. TD) and GMFCS level (I vs. II) subgroups. Test-retest reliability of the total 21 variables was examined using one-way repeated measures ANOVAs to check for differences among the three-trial means. Test-retest reliability over the 3 trials was additionally analyzed using intra-class coefficients (ICC (2, 1)) in 19 of the 21 variables as supported by the work of J. Weir; eAngle and mFreq were excluded from this testing since these variables had ranges that included negative values [20].

To assess concurrent validity, three trials were averaged and compared between devices by subject type subgroup (CP vs. TD) using Pearson correlations. Further concurrent validity testing was run using paired sample t-tests to examine differences in means between devices by subgroup (CP vs. TD). Discriminant validity was examined by independent sample t-tests to determine if significant differences existed between subject type and GMFCS level (I vs. II) for each variable on each device. To further assess discriminant validity, logistic regression was utilized to determine if the mean values from each device could differentiate between typically developing children and children with CP.

4. Results

Means and standard deviations for each group on each device can be found in Table 1. Test-retest reliability of the variables using one-way repeated measures ANOVAs found 18 of 21 variables to have no significant differences among the three-trial means, indicating good test-retest reliability. The only variables to have significant differences in trial means were in the CP group for AP average acceleration (aAcc-AP) on the force plate, and for ML average acceleration and ML average jerk (aAcc-ML, aJerk ML) on the pressure mat (Table 2 and Supplemental Table 1).

Test-retest reliability analysis using ICC (2,1) on 19 of the 21 variables, with exception of eAngle, and mFreq due to negative values, found 14 of the 19 variables had an ICC greater than 0.6, $p \leq .0005$

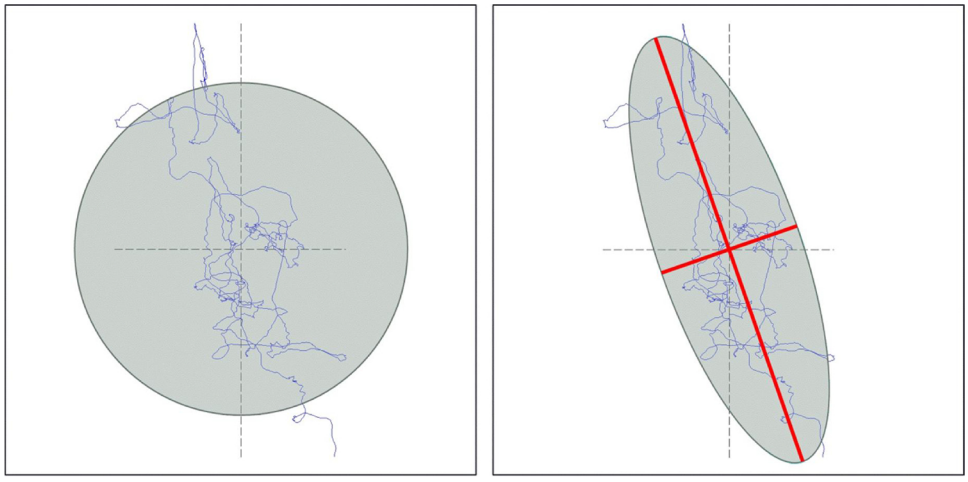

Fig. 5. Circle Area (cArea), Ellipse Area (eArea) and Ellipse Angle (eAngle).
cArea refers to the circular area created by the tracing of the CoP data points (Left figure).
eArea refers to the elliptical area created by the tracing of the CoP data points (Right figure).
eAngle is the angle of the major axis of the eArea on the Y (A/P) axis.

Table 1
Means and Standard Deviations of CoP Variables.

		Pressure Mat		Force Plate	
Variable	Units	Typically Developing	Cerebral Palsy	Typically Developing	Cerebral Palsy
aRadial-MLavg	mm	1.9 ± 1.0	4.6 ± 3.4	1.9 ± 1.0	4.3 ± 3.0
aRadial-APavg	mm	3.2 ± 1.1	5.8 ± 2.9	3.4 ± 1.1	5.7 ± 2.7
aRadial-OAavg	mm	4.1 ± 1.5	8.3 ± 4.6	4.2 ± 1.5	8.0 ± 4.2
aVel-MLavg	mm/s	5.2 ± 2.4	7.0 ± 3.3	6.0 ± 3.1	7.6 ± 3.9
aVel-APavg	mm/s	5.4 ± 1.7	7.2 ± 3.2	7.5 ± 2.3	9.1 ± 3.5
aVel-OAavg	mm/s	8.4 ± 3.2	11.2 ± 5.0	10.7 ± 4.2	13.2 ± 5.7
aAcc-MLavg	mm/s^2	238.1 ± 73.5	277.6 ± 87.8	174.9 ± 69.3	191.7 ± 64.5
aAcc-APavg	mm/s^2	165.4 ± 57.7	169.1 ± 55.3	214.6 ± 77.8	224.2 ± 77.2
aAcc-OAavg	mm/s^2	221.3 ± 73.1	246.5 ± 79.3	214.6 ± 81.0	224.6 ± 76.0
aJerk-MLavg	mm/s^3	22185.2 ± 6418.7	25918.5 ± 8194.9	14375.1 ± 4841.0	16090.0 ± 5499.5
aJerk-APavg	mm/s^3	14461.8 ± 5214.6	14494.8 ± 5152.8	17947.4 ± 6711.1	19020.6 ± 7209.5
aJerk-OAavg	mm/s^3	201134.0 ± 6424.1	22399.2 ± 7385.2	17484.4 ± 6420.9	18642.2 ± 6787.4
Range-MLavg	mm	11.8 ± 6.4	26.6 ± 18.5	13.3 ± 7.0	26.6 ± 17.4
Range-APavg	mm	18.4 ± 5.9	31.0 ± 14.9	20.0 ± 6.1	32.0 ± 14.2
SPL-avg	mm	234.5 ± 88.6	313.4 ± 140.4	300.7 ± 116.8	368.9 ± 158.6
cAreaavg	mm^2	225.0 ± 151.8	1021.0 ± 984.3	238.6 ± 159.0	948.0 ± 872.0
eAreaavg	mm^2	176.1 ± 141.2	858.0 ± 877.7	196.2 ± 153.1	821.1 ± 819.4
eAngleavg	Degree	−0.97 ± 15.35	4.36 ± 23.07	−1.84 ± 12.17	1.88 ± 24.55
mFreqavg	Hz	0.42 ± 0.13	0.34 ± 0.18	0.56 ± 0.15	0.43 ± 0.20
rFreqavg	Hz	0.36 ± 0.11	0.26 ± 0.09	0.43 ± 0.11	0.31 ± 0.12
sAreaavg	mm^2/s	12.3 ± 10.2	36.4 ± 34.0	15.9 ± 13.8	40.1 ± 36.0

indicating good test retest reliability (Table 2 and Supplemental Table 1) [21]. The AP average radial displacement (aRadial-AP) and the circle area (cArea) variables were found to have poor ICC values (less than 0.6) on both devices for both CP and TD groups. Range moved-AP (Range-AP), overall average radial displacement (aRadial-OA) and frequency revolve (rFreq) were found to have ICC values less than .6 on both devices for the TD group. Frequency revolve (rFreq) was also shown to have an ICC value less than .6 for the pressure mat in the CP group (Table 2 and Supplemental Table 1).

For concurrent validity, Pearson r correlations between the three-trial averages were assessed for all 21 variables, significant moderate to strong relationships were found between the force plate and mat for each group, $p \leq .001$. These correlations ranged from 0.727 to 0.992 for the typical group and from 0.509 to 0.994 for the CP group; the majority of these correlations were ≥.9. Concurrent validity was further examined by subject type with paired t-tests comparing the overall variable averages on each device. In the TD subgroup significant differences were found for 18 of 21 variables, $p \leq .018$ (Supplemental Table 2). For the CP group significant differences were identified for 16 of 21 variables, $p \leq .039$ (Supplemental Table 3).

Discriminant validity was examined by independent sample t-tests to determine significant differences between subgroups for each variable by device. Using the pressure mat, 13 variables were found to be significantly different in the CP vs. TD subgroup, $p \leq .022$ (Table 3). Using the force plate, 11 variables were found to be significantly different in the CP vs. TD subgroup, $p \leq .043$ (Supplemental Table 4). Discriminant validity was also examined between GMFCS levels for each device. Independent sample t-tests comparing GMFCS level I vs. II found significant differences in 8 of 21 variables using the pressure mat, $p \leq .05$ and in 6 of 21 variables using force plate data, $p \leq .043$ (Table 4).

To further assess discriminant validity, logistic regression was used to determine if the mean values from each device could differentiate between TD children and children with CP. On the pressure mat, 15 of 21 variables were found to significantly predict group membership, $p \leq .048$ (Supplemental Table 5). Specifically, all 3 average radial displacement variables (aRadial-OA, ML and AP) were found to have odds ratio (OR) of ≥ 1.58, 1.89 and 1.91 respectively. On the force plate, 11 of 21 variables were found to significantly predict group membership, $p \leq .036$. Again, all 3 average radial displacement variables (aRadial- OA, ML and AP) were found to have impressive OR values (1.61, 1.97 and 2.0 respectively). For frequency revolve both devices found an OR value of < .01, which indicates as the value increases by 1 the odds of being placed in the CP group decreases.

5. Discussion

To our knowledge a comprehensive reliability and validity study of available CoP variables published in the literature examining static standing balance in both typically developing and children with CP on a plantar pressure mat has not been undertaken. A primary goal of this study was to examine the efficacy of a plantar pressure mat as an alternative to testing on a force plate for collection of static standing balance data in children with CP. Following a review of the existing literature, 21 variables were chosen to calculate CoP from data collected on a plantar pressure mat with simultaneous collection on a force plate. Ultimately, this study identified that reliable and valid measures of static standing balance can be produced with a plantar pressure mat for typically developing and children with CP. We recognize that one limitation of this study is the homogenous nature of the CP group, and future research should expand to include other types of CP as well as other diagnoses.

Although a majority of the tested variables proved to be reliable on both devices and with both subgroups, it was important to determine which variables possessed both reliability and validity. A summary table was produced to give a global view of the reliability and validity of each variable to determine the most useful variables for each subgroup on each device (Table 5). The following 5 variables were found to have high test-retest reliability (ICC > 0.6) and possess discriminant validity between the subgroups (TD vs. CP) for both devices: aRadial-ML; Range-ML; aVel-AP; eArea; and sArea. Additionally, the eArea and sArea variables also had the ability to discriminate between GMFCS levels in the CP study group, with a small sample size.

Balance testing is an important component in treatment planning and outcome assessment for children with CP. This study provides the clinician with a small set of variables that can be tested on a portable device encouraging the utilization of balance assessment in a variety of settings. Due to the differences found between variable means on the two devices, subsequent balance testing on the same subject is recommended on the same type of device to accurately assess change. By providing portability and a streamlined evaluation, clinicians are more likely to use balance assessment as part of their therapy regimen

Table 2
Test-Retest Reliability of Pressure Mat.

Pressure Mat Variable	Units	$ICC_{(2,1)}$ with 95% CI				ANOVA (p-value*)		SEM	
		Typically Developing		Cerebral Palsy		Typically Developing	Cerebral Palsy	Typically Developing	Cerebral Palsy
			p-value*		p-value*				
aRadial-MLavg	mm	0.628 (0.435–0.784)	≤**0.0005**	0.662 (0.469–0.807)	≤**0.0005**	0.120	0.709	0.8	2.0
aRadial-APavg	mm	0.323 (0.098–0.557)	**0.002**	0.555 (0.345–0.735)	≤**0.0005**	0.814	0.455	1.1	2.3
aRadial-OAavg	mm	0.530 (0.317–0.717)	≤**0.0005**	0.720 (0.556–0.843)	≤**0.0005**	0.608	0.399	1.2	2.7
aVel-MLavg	mm/s	0.641 (0.451–0.793)	≤**0.0005**	0.834 (0.721–0.911)	≤**0.0005**	0.421	0.145	1.1	1.5
aVel-APavg	mm/s	0.741 (0.585–0.856)	≤**0.0005**	0.814 (0.691–0.899)	≤**0.0005**	0.744	0.355	0.8	1.6
aVel-OAavg	mm/s	0.683 (0.507–0.820)	≤**0.0005**	0.851 (0.748–0.920)	≤**0.0005**	0.527	0.163	1.4	2.2
aAcc-MLavg	mm/s^2	0.764 (0.617–0.870)	≤**0.0005**	0.726 (0.565–0.847)	≤**0.0005**	0.087	**0.027**	31.4	37.6
aAcc-APavg	mm/s^2	0.846 (0.740–0.917)	≤**0.0005**	0.719 (0.554–0.842)	≤**0.0005**	0.125	0.334	22.5	28.7
aAcc-OAavg	mm/s^2	0.809 (0.684–0.896)	≤**0.0005**	0.729 (0.568–0.848)	≤**0.0005**	0.093	0.073	28.5	34.3
aJerk-MLavg	mm/s^3	0.777 (0.636–0.877)	≤**0.0005**	0.701 (0.530–0.831)	≤**0.0005**	0.103	**0.035**	2857.8	3515.3
aJerk-APavg	mm/s^3	0.832 (0.718–0.909)	≤**0.0005**	0.729 (0.556–0.843)	≤**0.0005**	0.076	0.433	2203.7	2462.0
aJerk-OAavg	mm/s^3	0.810 (0.685–0.897)	≤**0.0005**	0.702 (0.532–0.832)	≤**0.0005**	0.099	0.126	2680.5	3192.7
Range-MLavg	mm	0.651 (0.464–0.799)	≤**0.0005**	0.686 (0.510–0.822)	≤**0.0005**	0.847	0.755	4.2	10.8
Range-APavg	mm	0.498 (0.280–0.694)	≤**0.0005**	0.691 (0.516–0.825)	≤**0.0005**	0.368	0.472	4.4	9.7
SPL-avg	mm	0.683 (0.507–0.820)	≤**0.0005**	0.851 (0.748–0.920)	≤**0.0005**	0.527	0.163	39.1	61.6
cAreaavg	mm^2	0.484 (0.265–0.684)	≤**0.0005**	0.549 (0.339–0.731)	≤**0.0005**	0.650	0.543	115.7	652.8
eAreaavg	mm^2	0.652 (0.465–0.800)	≤**0.0005**	0.621 (0.426–0.780)	≤**0.0005**	0.691	0.649	89.5	610.1
rFreqavg	Hz	0.549 (0.339–0.730)	≤**0.0005**	0.539 (0.327–0.723)	≤**0.0005**	0.250	0.154	0.08	0.07
sAreaavg	mm^2/s	0.627 (0.434–0.784)	≤**0.0005**	0.725 (0.563–0.846)	≤**0.0005**	0.823	0.692	5.2	22.1

*Significant at $p \leq 0.05$ **eAngle & mFreq not included due to negative values**.

Table 3
Discriminant Validity of Pressure Mat between TD and CP (t-tests).

Pressure Mat Variable	Units	Typically Developing Means (n = 30)	Cerebral Palsy Means (n = 30)	p-value*	95% CI of Mean Difference - Absolute Value
aRadial-MLavg	mm	1.9 ± 1.0	4.6 ± 3.4	≤**0.0005**	1.4 to 4.0
aRadial-APavg	mm	3.2 ± 1.1	5.8 ± 2.9	≤**0.0005**	1.4 to 3.7
aRadial-OAavg	mm	4.1 ± 1.5	8.3 ± 4.6	≤**0.0005**	2.4 to 5.9
aVel-MLavg	mm/s	5.2 ± 2.4	7.0 ± 3.3	**0.022**	0.3 to 3.3
aVel-APavg	mm/s	5.4 ± 1.7	7.2 ± 3.2	**0.007**	0.5 to 3.2
aVel-OAavg	mm/s	8.4 ± 3.2	11.2 ± 5.0	**0.012**	0.6 to 5.0
Range-MLavg	mm	11.8 ± 6.4	26.6 ± 18.5	≤**0.0005**	7.5 to 22.0
Range-APavg	mm	18.4 ± 5.9	31.0 ± 14.9	≤**0.0005**	6.8 to 18.6
SPLavg	mm	234.5 ± 88.6	313.4 ± 140.4	**0.012**	18.0 to 139.9
cAreaavg	mm^2	225.0 ± 151.8	1021.0 ± 984.3	≤**0.0005**	424.8 to 1167.1
eAreaavg	mm^2	176.1 ± 141.2	858.0 ± 877.7	≤**0.0005**	350.7 to 1013.1
rFreqavg	Hz	0.36 ± 0.11	0.26 ± 0.09	≤**0.0005**	0.15 to 0.05
sAreaavg	mm^2/s	12.3 ± 10.2	36.4 ± 34.0	**0.001**	11.0 to 37.3

*Significant at $p \leq 0.05$.

Table 4
Discriminant Validity of Pressure Mat between GMFCS Levels (t-tests).

	Units	GMFCS I Means (n = 17)	GMFCS II Means (n = 13)	p-value*	95% CI of Mean Differences - Absolute Values
Pressure Mat Variable					
aRadial-APavg	mm	4.8 ± 2.5	7.0 ± 2.9	**0.04**	0.1 to 4.2
aRadial-OAavg	mm	6.7 ± 3.8	10.2 ± 4.9	**0.036**	0.3 to 6.7
Range-MLavg	mm	20.5 ± 13.5	34.5 ± 21.6	**0.038**	0.8 to 27.2
Range-APavg	mm	26.3 ± 12.8	37.3 ± 15.5	**0.043**	0.4 to 21.6
cAreaavg	mm^2	656.5 ± 642.2	1497.6 ± 1165.0	**0.031**	86.0 to 1596.2
eAreaavg	mm^2	550.8 ± 590.6	1259.7 ± 1043.1	**0.042**	30.1 to 1387.6
mFreqavg	Hz	0.40 ± 0.19	0.27 ± 0.12	**0.04**	0.01 to 0.26
sAreaavg	mm^2/s	24.8 ± 20.9	51.7 ± 42.1	**0.05**	.04 to 53.8
Force Plate Variable					
aRadial-APavg	mm	4.8 ± 4.4	7.0 ± 2.8	**0.024**	0.3 to 4.1
aRadial-OAavg	mm	6.6 ± 3.4	9.9 ± 4.5	**0.029**	0.4 to 6.3
Range-APavg	mm	27.4 ± 11.8	38.2 ± 15.2	**0.036**	0.8 to 20.9
cAreaavg	mm^2	618.4 ± 570.6	1379.0 ± 1032.8	**0.027**	96.0 to 1425.3
eAreaavg	mm^2	530.5 ± 530.1	1201.2 ± 985.8	**0.04**	34.1 to 1307.4
sAreaavg	mm^2/s	27.3 ± 21.9	56.7 ± 44.4	**0.043**	1.0 to 57.7

*Significant at $p \leq 0.05$.

Table 5
Summary of Findings.

Variable	Reliability: Test-Retest				Validity: Discriminant					
	Typically Developing		Cerebral Palsy		TD vs CP (t-tests)		TD vs CP (regression)		GMFCS Level (t-tests)	
	Mat	FP	Mat	FP	Mat	FP	Mat	FP	Mat	FP
aRadial-MLavg	•	•	•	•	•	•	•	•		
aRadial-APavg					•	•	•	•	•	•
aRadial-OAavg			•	•	•	•	•	•	•	•
aVel-MLavg	•	•	•	•	•		•			
aVel-APavg	•	•	•	•	•	•	•	•		
aVel-OAavg	•	•	•	•	•		•			
aAcc-MLavg	•	•	•	•						
aAcc-APavg	•	•	•	•						
aAcc-OAavg	•	•	•	•						
aJerk-MLavg	•	•	•	•			•			
aJerk-APavg	•	•	•	•						
aJerk-OAavg	•	•	•	•						
Range-MLavg	•	•	•	•	•	•	•	•	•	
Range-APavg			•	•	•	•	•	•	•	•
SPLavg	•	•	•	•	•		•			
cAreaavg					•	•	•	•	•	•
eAreaavg	•	•	•	•	•	•	•	•	•	•
eAngleavg	•	•	•	•						
mFreqavg	•	•	•	•		•	•	•	•	
rFreqavg				•	•	•	•	•		
sAreaavg	•	•	•	•	•	•	•	•	•	•
# of Significant Variables	**16**	**16**	**18**	**19**	**13**	**11**	**15**	**11**	**8**	**6**
# of Variables Reliable **&** Valid for both subgroups					**8**	**6**	**10**	**6**	**4**	**2**

• indicates $p \leq 0.05$, or ICC > .6.

thereby increasing opportunity for outcomes analysis.

6. Conclusion

While motion labs typically use force plates for balance measurement, this study established that plantar pressure mats can be used for static standing balance testing. Reliable and valid measures were obtained with the Tekscan HR Plantar Pressure Mat, many of which have the ability to discriminate between children with CP and Typically Developing children. Five CoP measures show ability to perform equally well on either device and in both groups. In addition, a normative data set of means has been compiled for the 21 defined CoP measures used to assess static standing balance for both the Tekscan HR Mat and AMTI force plate. Although this study examined 21 CoP measures, concentrating future research on the five aforementioned variables may assist in determining if these CoP balance measures can accurately evaluate and report pre-post change after treatment interventions in the CP population. This pressure mat testing modality may prove useful in other diagnostic categories.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2018.08.012.

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