Test-retest reliability of a balance testing protocol with external perturbations in young healthy adults

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Abstract

External perturbations are utilized to challenge balance and mimic realistic balance threats in patient populations. The reliability of such protocols has not been established. The purpose was to examine test-retest reliability of balance testing with external perturbations. Healthy adults (n=34; mean age 23 years) underwent balance testing over two visits. Participants completed ten balance conditions in which the following parameters were combined: perturbation or non-perturbation, single or double leg, and eyes open or closed. Three trials were collected for each condition. Data were collected on a force plate and external perturbations were applied by translating the plate. Force plate center of pressure (CoP) data were summarized using 13 different CoP measures. Test-retest reliability was examined using intraclass correlation coefficients (ICC) and Bland-Altman plots. CoP measures of total speed and excursion in both anterior-posterior and medial-lateral directions generally had acceptable ICC values for perturbation conditions (ICC=0.46 to 0.87); however, many other CoP measures (e.g. range, area of ellipse) had unacceptable test-retest reliability (ICC<0.70). Improved CoP measures were present on the second visit indicating a potential learning effect. Non-perturbation conditions generally produced more reliable CoP measures than perturbation conditions during double leg standing, but not single leg standing. Therefore, changes to balance testing protocols that include external perturbations should be made to improve test-retest reliability and diminish learning including more extensive participant training and increasing the number of trials. CoP measures that consider all data points (e.g. total speed) are more reliable than those that only consider a few data points.

Key Words: balance, perturbation, fore plate, center of pressure, reliability

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Balance is frequently assessed in both research and clinical contexts in a variety of populations, and many different tools exist to quantify balance [1-3]. Balance deficits likely play a role in diminished physical function and place individuals at a greater fall risk [4]. Stable and reliable measures are needed if changes in balance are to be assessed in response to treatment, changes in disease status, or aging.

Force plates are frequently used to quantify balance. They measure center of pressure (CoP) and numerous methods exist to reduce complex CoP patterns to more manageable, discrete measures (e.g. standard deviation of CoP) [3,5]. Additionally, different protocols exist with varying conditions including leg position (e.g. double or single leg stance), eyes open or closed, and surface type [6]. Reliability of CoP measures has been examined in static situations when patients are expected to remain motionless. Studies found that CoP measures demonstrate moderate to good test-retest reliability over different balance conditions [7-9]. Other studies have found poor to fair test-retest reliability [10,11]. Discrepancies are likely due to differences in CoP measures, balance testing conditions, data processing, and study samples. However, there is sufficient evidence that force plate measures of balance provide acceptable reliability in various populations [7,8,12,13].

Balance can be further challenged by inducing either an internal or external perturbation. These balance threats should be considered because they occur within a range of daily activities such as standing on a moving bus. Force plates placed on translating platforms provide an opportunity to examine balance recovery following perturbations in a controlled and standardized manner. For instance, patients after anterior cruciate ligament reconstruction and patients with knee osteoarthritis have

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demonstrated impairments in balance responses to external perturbations compared to healthy controls [14,15]. Muscle responses to these perturbations have also been investigated in healthy and patient populations [16,17]. External perturbations place greater demands on body systems responsible for maintaining balance and could be more sensitive at identifying balance deficits in patients compared to static tests.

Although balance responses to external perturbations are being measured, the reliability of these measures has not been established. Examining reliability is important if these measures are to be used to compare groups or examine change over time in response to disease progression or treatment. Furthermore, evidence exists that there is a learning effect in balance responses to external perturbations which could negatively impact reliability [14,18]. Therefore, the primary objective was to examine test-retest reliability of a balance testing protocol that includes external perturbations in healthy adults. Secondary objectives were to compare test-retest reliability between perturbation and non-perturbation tasks, and to comprehensively examine test-retest reliability of different CoP measures.

2. Methodology

2.1 Study Design and Participants

Healthy participants between 18-50 years of age were recruited using convenience sampling for this test-retest reliability study. They were recruited from the local community using advertisements and word of mouth. Exclusion criteria included: recent lower extremity injury (<1 year), current lower extremity pain, previous lower extremity fracture, previous reconstructive surgery in the lower extremity, balance deficits (e.g. vestibular dysfunction), medical conditions affecting balance, and neurological

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conditions. Written, informed consent was obtained from participants and the study was approved by the local research ethics board.

A sample size calculation was performed using data from a previous test-retest reliability study of healthy participants that demonstrated intraclass correlation coefficients (ICC) greater than 0.80 for most CoP derived measures during non-perturbation balance conditions [7,19]. The required sample was 33 participants assuming ICC=0.80, 95% confidence interval rate of 0.25, and two visits. To account for potential drop-out, a 5% attrition rate was added resulting in 35 participants. One participant did not complete both visits. Thus, 34 participants (18 women) were included in analyses. The sample had a mean (standard deviation) age of 23(2) years, height of 1.72 (0.08) m, weight of 63.93 (9.52) kg, and body mass index of 21.5 (2.2) kg/m^2.

2.2 Data Collection

Data were collected over two visits separated by three to 14 days. Testing was performed on a force plate (OR6-6-2K-7575, AMTI) sampled at 1000 Hz securely attached to a custom perturbation platform (H2W Technologies) and these equipment moved in unison. The perturbation platform can translate in anterior-posterior and medial-lateral directions. Four reflective markers were placed on the force plate corners to determine when force plate translation began and ended. Reflective marker position was recorded using an eight camera system (T20, Vicon) sampled at 100 Hz. Marker and force plate data were recorded using commercial software (Vicon Nexus v1.8.5).

Ten balance conditions were examined. This included six perturbation conditions with eyes open: 1) double leg stance with anterior perturbation, 2) double leg stance with posterior perturbation, 3) double leg stance with right perturbation, 4) double leg stance

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with left perturbation, 5) single leg stance with anterior perturbation, and 6) single leg stance with posterior perturbation. Non-perturbation conditions included: 7) double leg stance with eyes open, 8) double leg stance with eyes closed, 9) single leg stance with eyes open, and 10) single leg stance with eyes closed. The balance conditions were based on pilot testing and previous studies [8,12,14,18,20], and were tasks that participants could consistently complete. Participants were placed at the center of the force plate, barefoot with feet at shoulder width, and hands on hips. They were instructed to stare at a marked X on the wall at eye level, and they wore a safety harness. For single leg stance conditions, test leg was randomly chosen (17 right, 17 left) and it was the same leg for both visits. The non-study knee was bent to 90^{o} with 0^{o} of hip flexion, while the study knee remained in slight flexion. Data recording for double leg stance conditions lasted 35 s with no rest between trials; single leg stance conditions lasted 15 s and a standard rest period of 20 s was provided between these trials. Also, participants were allowed additional rest as required and they were prompted to take this rest to minimize fatigue. For perturbation conditions, external perturbations occurred within the first 3 s of data recording, which was chosen by an investigator. External perturbation parameters were initially based on previous research, but were modified based on pilot testing; the platform accelerated at a maximum of $600mm/s^2$ with an amplitude proportional to each participant's body height (perturbation amplitude = 0.06 x height) [14,18]. Each condition was performed three times, for a total of 30 trials [21]. If the participant was unable to maintain the position (i.e. fall, step) during a given trial, it was discarded and restarted. Participants had two attempts to successfully complete each trial. The number of discarded trials was recorded.

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2.3 Procedure

Demographic information was collected including age, sex, height, weight, and body mass index. The testing protocol was explained to participants and they completed one practice trial for each condition at the beginning of the first visit. Practice was provided since previous studies have found differences between the first trial and subsequent trials for balance responses to external perturbations indicating a learning effect [14,18]. Participants then completed either all single leg or all double leg stance conditions first and the order (single vs. double) was randomized. The order of testing was also randomized for all condition trials within single leg or double leg conditions including eye (open vs. closed) and perturbation conditions. Thus, participants were unaware if each trial was going to include an external perturbation and the perturbation direction. Each participant had their own unique sequence of balance conditions, and they underwent the same order of testing, by the same researchers, at both visits.

2.4 Data Processing

Data were processed in MATLAB version 7.14 (Mathworks). Force plate CoP data were low pass filtered with a recursive 4th order Butterworth filter with a cut-off frequency of 10 Hz [13]. CoP data were also down sampled from 1000 to 100 Hz in order to have a sampling frequency consistent with previous research [14,18,22]. Trial lengths were 15 and 35 s for single and double leg conditions respectively. However, in post-processing only the first 10 s (single leg) and 30 s (double leg) were used in the analysis for non-perturbation conditions. For external perturbation conditions, 10 s (single leg) and 30 s (double leg) of data were analyzed after the force plate stopped moving. The threshold speed for determining when the force plate started and stopped moving was 2

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mm/s, and this was also visually check by plotting the force plate reflective marker trajectories. From force plate data, different CoP measures were calculated based on measures commonly used in research. Descriptions of CoP measures and appropriate references are provided in Table 1. CoP measures were determined for each trial and were averaged over 3 trials for each condition.

2.5 Statistical Analysis

Descriptive statistics of demographic variables, number of discarded trials, and CoP measures were calculated. Test-retest reliability of CoP measures was examined using ICC (2, k) which determines relative reliability or the ability of a measure to distinguish among participants [23]. ICC values were interpreted as acceptable if they were equal to or greater than 0.70 which is considered the minimal standard of acceptable test-retest reliability for group data [24]. Measurement error for CoP measures was quantified using standard error of measurement (SEM) with 95% confidence intervals [25]. This provides a measure of absolute reliability or error in an individual score in its original units. Bland-Altman plots were used to plot the difference in a CoP measure between two visits against the mean of the visits [26]. Data analyses were computed with SPSS version 20 (IBM).

3. Results

3.1 Discarded Trials

On average, only two and one trials were discarded for each participant on the first and second visit respectively due to their inability to maintain balance. The maximum number of discarded trials for a participant visit was six. Conditions that produced the highest frequency of discarded trials across the sample over both visits were

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single leg stance with eyes closed (37 out of 204 trials), and single leg stance with posterior perturbation (18 out of 204 trials) or anterior perturbation (17 out of 204 trials). Each remaining condition produced less than seven discarded trials (out of a possible 204).

3.2 Test-Retest Reliability of Perturbation Conditions

Mean CoP measures, ICC values, and SEM values for double and single leg perturbation conditions are provided in Table 2 and 3 respectively. A graphical representation of ICC values is also presented in Supplemental Figure A. CoP measures for perturbations conditions generally had unacceptable test-retest reliability. Double leg stance with right perturbation produced CoP measures with the highest ICC values (ICC=0.52 to 0.83) with 8 of 13 CoP measures having acceptable test-retest reliability (ICC≥0.70). Double leg stance with anterior perturbation (ICC=0.14 to 0.66; 0 of 13 CoP measures had ICC≥0.70) produced the lowest ICC values. Generally, SEM values across all CoP measures and conditions (Table 2 and 3) were large in relation to the mean scores.

An example Bland-Altman plot is provided in Figure 1, and remaining Bland-Altman plots for perturbations conditions are provided in Supplemental Figure B. These plots and Tables 2-3 demonstrated consistently lower CoP measures, indicating improved balance, during the second visit. This is a potential learning effect. Outliers were noted for some perturbation conditions. These participants had large errors between visits and substantially higher CoP measures for some conditions (Figure 1, Supplemental Figure B). Removing outliers and re-analyzing data did substantially change some ICC values

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(Supplemental Table). However, removing outliers most often produced ICC value changes less than 0.10 (Supplemental Table).

3.3 Comparison of Perturbations and Non-Perturbations Conditions

Mean values for CoP measures, ICC values, and SEM values for double and single leg non-perturbation conditions are provided in Table 4. Generally, non-perturbation conditions produced higher ICC values than perturbation conditions for double leg stance (Table 2). Specifically, non-perturbation double leg stance with eyes open (ICC=0.59 to 0.81; 5 of 13 CoP measures had ICC≥0.70) produced CoP measures with higher ICC values than double leg stance with anterior perturbation (ICC=0.14 to 0.66; 0 of 13 CoP measures had ICC≥0.70) and posterior perturbation (ICC=0.20 to 0.78; 3 of 13 CoP measures had ICC≥0.70). The exception was double leg stance with right perturbation which produced CoP measures with acceptable test-rest reliability (ICC=0.52 to 0.83, 8 of 13 CoP measures had ICC≥0.70). There was no clear pattern with single leg conditions with non-perturbation (Table 4) and perturbation (Table 3) conditions producing CoP measures with similar ICC values.

When examining measurement error (Table 2-4), double leg stance with eyes open produced CoP measures with lower SEM values, indicating decreased measurement error, than most double leg stance perturbation conditions, except for right perturbation. There was no clear trend when comparing double leg stance with eyes closed to double leg stance perturbation conditions. Similarly, single leg stance with eyes open, but not closed, generally produced CoP measures with lower SEM values than single leg stance perturbation conditions.

3.4 Comparison of CoP Measures

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Examining test-retest reliability of CoP measures across conditions (Table 2-4) demonstrated that CoP measures with the highest ICC values were Total Speed$_{AP}$ (ICC=0.46 to 0.87; 5 of 10 had ICC≥0.70), Total Speed$_{ML}$ (ICC=0.56 to 0.85; 7 of 10 had ICC≥0.70), Excursion$_{AP}$ (ICC=0.51 to 0.87; 6 of 10 had ICC≥0.70), and Excursion$_{ML}$ (ICC=0.57 to 0.85; 7 of 10 had ICC≥0.70). The lowest ICC values were produced by Range$_{AP}$, Range$_{ML}$, and Area.

4. Discussion

External perturbations have been applied during balance tasks to further challenge patients and mimic realistic balance threats [14,15]. Current findings demonstrate that healthy adults can maintain balance during external perturbation and that the testing protocol was feasible. The highest failure rate for any condition was only 9% (18 out of 204 trials) which was for single leg stance with posterior perturbation. Many CoP measures calculated after perturbations did not demonstrate acceptable test-retest reliability. However, some CoP measures (Total Speed, Excursion) demonstrated acceptable test-retest reliability across many perturbation conditions, and are the recommended CoP measures for similar protocols. Despite having acceptable ICC values, SEM values were high across measures and conditions. These findings indicate some CoP measures can be used to distinguish amongst individuals (e.g. comparing different groups) but are not appropriate when examining change in only one individual. Furthermore, a potential learning effect was present, and participants had improved CoP measures at second visits. Modifications should be made to future balance protocols with external perturbations to improve test-retest reliability.

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Previous studies investigating balance responses to external perturbation also demonstrated a learning effect. Specifically, the first of three trials during perturbation conditions produced the highest CoP values (e.g. reaction time) in patients with an anterior cruciate ligament deficiency or after reconstruction [14,18]. Current findings demonstrated learning between visits in healthy adults, which might represent neuromuscular adaptations to the balance task. This was despite providing one practice trial for each condition prior to data collection. More extensive training is warranted when evaluating balance responses to external perturbations. Potential training strategies include providing more practice trials prior to testing or implementing a separate training session that occurs before data collection. Increasing the number of trials for each condition has also previously shown to improve test-retest reliability [27]. Furthermore, it is not clear how perturbation parameters (e.g. platform acceleration) impact reliability and this should be examined. By diminishing the learning effect, then differences or improvements in balance can be attributed to group differences or treatment response after an intervention (e.g. balance training) and not to learning.

Generally, double leg perturbation conditions had lower test-retest reliability than non-perturbation conditions. The novelty of the perturbations and a learning effect likely account for this finding. However, single leg perturbation and non-perturbation conditions demonstrated similar test-retest reliability. The reason for this finding is not clear, but perhaps single leg standing induced additional balance demands which resulted in less stable CoP measures. Double and single leg non-perturbation conditions produced CoP measures with similar test-retest reliability compared to many previous studies of healthy adults [8,10,11,13,22,28]. However, other studies have demonstrated more

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reliable CoP measures [9,21]. Differences in balance conditions, testing protocol, instrumentation, data processing, sample characteristics, and type of CoP measures likely account for these discrepancies.

There are numerous ways to reduce complexity of CoP data, and various methods can impact test-retest reliability of CoP measures. In the current study, CoP measures of total speed (Total $Speed_{AP}$, Total $Speed_{ML}$) and excursion ($Excursion_{AP}$, $Excursion_{ML}$) produced the highest test-retest reliability. Total speed and excursion are essentially capturing the same information since total speed is excursion divided by time. These measures utilize all CoP data points by calculating the distance between consecutive data points and summing these distances. In comparison, measures such as range between maximum and minimum values ($Range_{AP}$) only utilize two data points, and were the least reliable. Thus, CoP measures that consider all data points had higher test-retest reliability. Similar findings were previously demonstrated in other studies [10,12,28]. CoP measures that consider all data points, such as total speed and excursion (i.e. path length), are more stable and should be considered when assessing expected changes in balance over time.

4.1 Limitations

Participants were young, healthy adults and results are not necessarily generalizable to older adults or patient populations. Another limitation is that participants reported fatigue during testing. This was not objectively measured and it might have impacted performance. However, a standard rest period was provided during single leg test conditions and additional rest was provided when requested. Only one set of perturbation parameters (e.g. acceleration, amplitude) was tested and future research should examine how varying perturbation parameters impact reliability.

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5. Conclusions

Measures of total speed and excursion demonstrated acceptable test-retest reliability for many balance conditions indicating that CoP measures which consider all data points should be utilized; however, most other CoP measures demonstrated unacceptable test-retest reliability when evaluating balance with external perturbations. Improved CoP measures on the second visit indicated that a learning effect partially accounted for between visit differences. Changes to the protocol should be made to improve test-retest reliability and limit learning including more extensive participant training and increasing the number of trials. Future studies should adapt the protocol and examine reliability in patient populations.

Conflicts of interest: none

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Table 1: A description of the center of pressure (CoP) measures.

CoP Measure	Description
Range_{AP}	Difference between maximum and minimum CoP position in the anterior-posterior direction [3]
Range_{ML}	Difference between maximum and minimum CoP position in the medial-lateral direction [3]
Excursion_{AP}	Absolute length of the CoP path movements (i.e. sum of distance between consecutive data points) in the anterior-posterior direction [3]
Excursion_{ML}	Absolute length of the CoP path movements (i.e. sum of distance between consecutive data points) in the medial-lateral direction [3]
Mean Excursion_{AP}	The mean of the absolute distances between the average CoP position and instantaneous CoP position in the anterior-posterior direction [5]
Mean Excursion_{ML}	The mean of the absolute distances between the average CoP position and instantaneous CoP position in the medial-lateral direction [5]
SD_{AP}	Standard deviation of the CoP position in the anterior-posterior direction [5]
SD_{ML}	Standard deviation of the CoP position in the medial-lateral direction [5]
Area	The area of an ellipse that captures 95% of the data points [3]
Max Speed_{AP}	The maximum of the absolute speed between adjacent CoP points in the anterior-posterior direction [5]
Max Speed_{ML}	The maximum of the absolute speed between adjacent CoP points in the medial-lateral direction [5]
Total Speed_{AP}	Excursion_{AP} divided by collection time [3]
Total Speed_{ML}	Excursion_{ML} divided by collection time [3]

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Table 2: Descriptive statistics and reliability of the center of pressure (CoP) measures for double leg perturbation conditions.

Condition	CoP Variable	Visit 1 Mean (SD)	Visit 2 Mean (SD)	ICC (95% CI)	SEM (95% CI)
Double Leg Anterior Perturbation	$Range_{AP}$ (mm)	77.14 (20.27)	53.47 (14.20)	0.30 (-0.20, 0.62)	14.35 (11.58, 18.86)
	$Range_{ML}$ (mm)	28.86 (29.23)	19.90 (7.27)	0.14 (-0.63, 0.56)	20.42 (16.48, 26.84)
	$Excursion_{AP}$ (mm)	1134.29 (325.20)	940.79 (245.67)	0.66 (0.15, 0.85)	183.84 (148.32, 241.64)
	$Excursion_{ML}$ (mm)	410.84 (244.58)	332.59 (105.95)	0.57 (0.16, 0.78)	143.08 (115.43, 188.06)
	Mean $Excursion_{AP}$ (mm)	5.38 (1.92)	4.80 (1.73)	0.50 (0.03, 0.75)	1.48 (1.19, 1.94)
	Mean $Excursion_{ML}$ (mm)	2.28 (1.64)	1.78 (0.85)	0.48 (-0.01, 0.73)	1.07 (0.87, 1.41)
	SD_{AP} (mm)	8.00 (2.39)	6.65 (2.10)	0.41 (-0.09, 0.70)	1.88 (1.52, 2.48)
	SD_{ML} (mm)	3.46 (3.12)	2.49 (1.08)	0.28 (-0.37, 0.63)	2.13 (1.71, 2.79)
	Area (mm^2)	583.86 (871.81)	323.76 (259.51)	0.24 (-0.44, 0.61)	594.16 (479.35, 780.99)
	Max $Speed_{AP}$ (mm/s)	384.12 (116.54)	291.50 (67.73)	0.59 (-0.15, 0.84)	59.08 (47.66, 77.66)
	Max $Speed_{ML}$ (mm/s)	141.21 (141.91)	104.00 (44.17)	0.21 (-0.52, 0.60)	98.37 (79.36, 129.30)
	Total $Speed_{AP}$ (mm/s)	38.77 (10.43)	31.36 (8.19)	0.64 (0.02, 0.85)	5.82 (4.70, 7.65)
	Total $Speed_{ML}$(mm/s)	14.04 (8.09)	11.09 (3.53)	0.56 (0.15, 0.78)	4.73 (3.81, 6.21)
Double Leg Posterior Perturbation	$Range_{AP}$ (mm)	67.01 (18.81)	48.33 (10.78)	0.24 (-0.21, 0.57)	13.41 (10.82, 17.63)
	$Range_{ML}$ (mm)	21.90 (8.41)	18.94 (7.10)	0.53 (0.10, 0.76)	6.11 (4.93, 8.04)
	$Excursion_{AP}$ (mm)	1151.65 (299.41)	1036.26 (309.77)	0.51 (0.05, 0.75)	243.95 (196.81, 320.65)
	$Excursion_{ML}$ (mm)	599.40 (182.19)	541.32 (205.26)	0.62 (0.25, 0.81)	143.15 (115.49, 188.16)
	Mean $Excursion_{AP}$ (mm)	5.02 (1.45)	4.41 (1.96)	0.33 (-0.30, 0.66)	1.54 (1.24, 2.02)
	Mean $Excursion_{ML}$ (mm)	1.89 (0.91)	1.61 (0.87)	0.78* (0.56, 0.89)	0.51 (0.42, 0.68)
	SD_{AP} (mm)	7.30 (1.97)	6.09 (2.29)	0.31 (-0.25, 0.64)	1.90 (1.53, 2.50)

Robbins SM, Caplan RM, Aponte DI, St-Onge N (2017). Test-retest reliability of a balance testing protocol with external perturbations in healthy adults. Gait & Posture, 58, 433-439. doi: 10.1016/j.gaitpost.2017.09.007.

	SD_{ML} (mm)	2.63 (1.14)	2.27 (1.12)	0.77* (0.53, 0.89)	0.67 (0.54, 0.88)
	Area (mm^2)	356.39 (209.93)	263.18 (189.10)	0.52 (0.07, 0.75)	157.43 (127.01, 206.93)
	Max $Speed_{AP}$ (mm/s)	392.55 (118.80)	306.75 (54.62)	0.20 (-0.29, 0.55)	84.84 (68.45, 111.52)
	Max $Speed_{ML}$ (mm/s)	178.44 (33.31)	172.87 (29.25)	0.74* (0.48, 0.87)	20.10 (16.22, 26.42)
	Total $Speed_{AP}$ (mm/s)	39.10 (9.32)	34.54 (10.33)	0.46 (-0.02, 0.72)	8.07 (6.51, 10.60)
	Total $Speed_{ML}$(mm/s)	20.31 (5.73)	18.04 (6.88)	0.58 (0.19, 0.79)	4.77 (3.85, 6.27)
Double Leg Right Perturbation	$Range_{AP}$ (mm)	32.71 (8.20)	29.14 (9.49)	0.71* (0.41, 0.86)	5.69 (4.59, 7.48)
	$Range_{ML}$ (mm)	98.54 (26.12)	68.14 (24.91)	0.59 (-0.23, 0.86)	13.60 (10.98, 17.88)
	$Excursion_{AP}$ (mm)	537.43 (132.66)	506.84 (125.20)	0.74* (0.49, 0.87)	81.51 (65.76, 107.15)
	$Excursion_{ML}$ (mm)	385.99 (96.85)	326.72 (82.17)	0.78* (0.12, 0.92)	41.96 (33.85, 55.15)
	Mean $Excursion_{AP}$ (mm)	4.38 (1.46)	4.04 (1.86)	0.78* (0.56, 0.89)	1.00 (0.80, 1.31)
	Mean $Excursion_{ML}$ (mm)	2.79 (1.03)	2.37 (1.09)	0.68 (0.36, 0.84)	0.71 (0.58, 0.94)
	SD_{AP} (mm)	5.60 (1.81)	5.10 (2.22)	0.81* (0.63, 0.91)	1.11 (0.89, 1.46)
	SD_{ML} (mm)	6.63 (2.21)	5.09 (1.91)	0.71* (0.04, 0.89)	1.13 (0.91, 1.49)
	Area (mm^2)	694.45 (414.08)	485.26 (344.47)	0.83* (0.31, 0.94)	164.44 (132.67, 216.15)
	Max $Speed_{AP}$ (mm/s)	163.50 (38.41)	159.26 (31.68)	0.52 (0.04, 0.76)	28.40 (22.92, 37.34)
	Max $Speed_{ML}$ (mm/s)	405.12 (136.45)	275.34 (97.23)	0.56 (-.0.21, 0.83)	73.37 (59.20, 96.45)
	Total $Speed_{AP}$ (mm/s)	18.26 (4.13)	16.89 (4.17)	0.70* (0.41, 0.85)	2.74 (2.21, 3.60)
	Total $Speed_{ML}$(mm/s)	13.09 (2.97)	10.89 (2.74)	0.75* (-0.06, 0.92)	1.34 (1.08, 1.76)
Double Leg Left Perturbation	$Range_{AP}$ (mm)	41.56 (8.13)	41.32 (8.95)	0.60 (0.19, 0.80)	6.51 (5.25, 8.56)
	$Range_{ML}$ (mm)	92.77 (20.76)	66.88 (20.05)	0.46 (-0.23, 0.77)	13.90 (11.21, 18.27)
	$Excursion_{AP}$ (mm)	1276.54 (467.14)	1136.81 (420.62)	0.73* (0.46, 0.86)	282.59 (227.98, 371.44)
	$Excursion_{ML}$ (mm)	390.24 (106.95)	339.62 (104.02)	0.76* (0.73, 0.89)	59.45 (47.97, 78.15)

Robbins SM, Caplan RM, Aponte DI, St-Onge N (2017). Test-retest reliability of a balance testing protocol with external perturbations in healthy adults. Gait & Posture, 58, 433-439. doi: 10.1016/j.gaitpost.2017.09.007.

Mean Excursion$_{AP}$ (mm)	4.09 (1.25)	4.13 (1.56)	0.61 (0.21, 0.81)	1.06 (0.86, 1.39)
Mean Excursion$_{ML}$ (mm)	2.63 (1.05)	2.13 (1.01)	0.42 (-0.08, 0.70)	0.86 (0.70, 1.14)
SD$_{AP}$ (mm)	5.37 (1.48)	5.41 (1.83)	0.65 (0.29, 0.83)	1.21 (0.98, 1.59)
SD$_{ML}$ (mm)	6.11 (1.77)	4.84 (1.46)	0.32 (-0.19, 0.63)	1.41 (1.14, 1.86)
Area (mm^2)	616.55 (308.56)	496.55 (257.37)	0.60 (0.23, 0.80)	207.98 (167.79, 273.37)
Max Speed$_{AP}$ (mm/s)	483.54 (95.29)	446.09 (97.94)	0.68 (0.35, 0.84)	65.44 (52.79, 86.01)
Max Speed$_{ML}$ (mm/s)	404.23 (109.20)	274.62 (86.29)	0.37 (-0.21, 0.69)	75.34 (60.78, 99.03)
Total Speed$_{AP}$ (mm/s)	43.29 (15.19)	37.89 (14.02)	0.72* (0.43, 0.86)	9.32 (7.52, 12.25)
Total Speed$_{ML}$ (mm/s)	13.22 (3.37)	11.32 (3.47)	0.74* (0.33, 0.87)	1.95 (1.57, 2.56)

SD, standard deviation; ICC, intraclass correlation coefficient model (2, k); SEM, standard error of measurement; CI, confidence interval

*Acceptable test-retest reliability (ICC≥0.70)

Robbins SM, Caplan RM, Aponte DI, St-Onge N (2017). Test-retest reliability of a balance testing protocol with external perturbations in healthy adults. Gait & Posture, 58, 433-439. doi: 10.1016/j.gaitpost.2017.09.007.

Table 3: Descriptive statistics and reliability of the center of pressure (CoP) measures for the single leg perturbation conditions.

Condition	CoP Variable	Visit 1 Mean (SD)	Visit 2 Mean (SD)	ICC (95% CI)	SEM (95% CI)
Single Leg Anterior Perturbation	$Range_{AP}$ (mm)	85.84 (25.14)	64.38 (16.76)	0.37 (-0.16, 0.68)	17.36 (14.00, 22.81)
	$Range_{ML}$ (mm)	36.49 (11.74)	30.20 (4.94)	0.12 (-0.50, 0.52)	8.64 (6.97, 11.36)
	$Excursion_{AP}$ (mm)	734.82 (158.18)	668.77 (142.69)	0.82* (0.53, 0.92)	73.37 (59.19, 96.44)
	$Excursion_{ML}$ (mm)	387.60 (87.46)	342.80 (59.19)	0.67 (0.23, 0.85)	48.04 (38.76, 63.15)
	Mean $Excursion_{AP}$ (mm)	8.72 (3.29)	7.04 (1.53)	0.40 (-0.10, 0.69)	2.15 (1.73, 2.82)
	Mean $Excursion_{ML}$ (mm)	5.91 (2.23)	4.97 (0.90)	0.19 (-0.47, 0.57)	1.60 (1.29, 2.10)
	SD_{AP} (mm)	12.90 (4.88)	9.67 (2.20)	0.40 (-0.12, 0.69)	3.08 (2.48, 4.04)
	SD_{ML} (mm)	7.49 (2.84)	6.20 (1.11)	0.10 (-0.60, 0.52)	2.09 (1.69, 2.75)
	Area (mm^2)	1874.44 (1375.43)	1128.79 (420.10)	0.18 (-0.40, 0.55)	952.71 (768.63, 1252.29)
	Max $Speed_{AP}$ (mm/s)	545.81 (199.36)	418.54 (153.77)	0.36 (-0.16, 0.66)	152.54 (123.06, 200.50)
	Max $Speed_{ML}$ (mm/s)	267.49 (110.62)	204.73 (52.05)	0.30 (-0.22, 0.63)	76.24 (61.51, 100.21)
	Total $Speed_{AP}$ (mm/s)	73.50 (15.79)	66.88 (14.27)	0.82* (0.53, 0.92)	7.33 (5.92, 9.64)
	Total $Speed_{ML}$(mm/s)	38.77 (8.73)	34.28 (5.92)	0.67 (0.23, 0.85)	4.80 (3.87, 6.31)
Single Leg Posterior Perturbation	$Range_{AP}$ (mm)	71.27 (19.42)	56.88 (12.86)	0.52 (-0.06, 0.78)	11.84 (9.55, 15.56)
	$Range_{ML}$ (mm)	32.53 (6.03)	30.83 (5.24)	0.60 (0.21, 0.80)	4.24 (3.42, 5.57)
	$Excursion_{AP}$ (mm)	772.86 (163.92)	749.66 (150.45)	0.84* (0.68, 0.92)	82.54 (66.59, 108.50)
	$Excursion_{ML}$ (mm)	442.69 (90.98)	445.85 (98.02)	0.85* (0.70, 0.93)	48.98 (39.52, 64.38)
	Mean $Excursion_{AP}$ (mm)	8.40 (3.00)	7.26 (1.74)	0.62 (0.25, 0.81)	1.75 (1.41, 2.30)
	Mean $Excursion_{ML}$ (mm)	5.22 (1.19)	5.16 (1.11)	0.61 (0.20, 0.80)	0.87 (0.70, 1.14)
	SD_{AP} (mm)	11.54	9.63	0.61	2.24

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	(3.88)	(2.32)	(0.18, 0.81)	(1.81, 2.95)
SD_{ML} (mm)	6.57 (1.40)	6.40 (1.31)	0.62 (0.23, 0.81)	1.01 (0.82, 1.33)
Area (mm^2)	1447.18 (766.66)	1166.88 (506.28)	0.61 (0.24, 0.80)	471.27 (380.21, 619.46)
Max $Speed_{AP}$ (mm/s)	456.49 (160.74)	395.17 (90.35)	0.46 (-0.03, 0.72)	107.44 (86.68, 141.23)
Max $Speed_{ML}$ (mm/s)	252.33 (57.88)	231.02 (50.18)	0.72* (0.43, 0.86)	34.17 (27.56, 44.91)
Total $Speed_{AP}$ (mm/s)	77.29 (16.39)	74.97 (15.05)	0.84* (0.68, 0.92)	8.25 (6.66, 10.85)
Total $Speed_{ML}$ (mm/s)	44.27 (9.10)	44.58 (9.80)	0.85* (0.70, 0.93)	4.90 (3.95, 6.44)

SD, standard deviation; ICC, intraclass correlation coefficient model (2, k); SEM, standard error of measurement; CI, confidence interval

*Acceptable test-retest reliability (ICC≥0.70)

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Table 4: Descriptive statistics and reliability of the center of pressure (CoP) measures for double and single leg non-perturbation conditions.

Condition	CoP Variable	Visit 1 Mean (SD)	Visit 2 Mean (SD)	ICC (95% CI)	SEM (95% CI)
Double Leg Eyes Opened	$Range_{AP}$ (mm)	34.05 (10.00)	30.95 (6.20)	0.62 (0.26, 0.81)	6.02 (4.86, 7.91)
	$Range_{ML}$ (mm)	15.25 (5.63)	14.67 (5.68)	0.70* (0.40, 0.85)	3.85 (3.11, 5.06)
	$Excursion_{AP}$ (mm)	1097.37 (379.64)	978.10 (343.15)	0.64 (0.29, 0.82)	260.11 (209.85, 341.89)
	$Excursion_{ML}$ (mm)	516.81 (194.86)	446.78 (175.38)	0.71* (0.42, 0.86)	119.65 (96.53, 157.28)
	Mean $Excursion_{AP}$ (mm)	4.54 (1.62)	3.89 (1.29)	0.59 (0.20, 0.79)	1.08 (0.87, 1.42)
	Mean $Excursion_{ML}$ (mm)	1.60 (0.74)	1.63 (0.95)	0.74* (0.48, 0.87)	0.55 (0.44, 0.72)
	SD_{AP} (mm)	5.70 (1.99)	4.92 (1.54)	0.62 (0.25, 0.81)	1.27 (1.03, 1.67)
	SD_{ML} (mm)	2.12 (0.90)	2.11 (1.08)	0.77* (0.53, 0.88)	0.62 (0.50, 0.81)
	Area (mm^2)	231.86 (164.15)	195.46 (140.30)	0.62 (0.24, 0.81)	113.18 (91.31, 148.76)
	Max $Speed_{AP}$ (mm/s)	296.51 (44.33)	284.89 (51.69)	0.81* (0.62, 0.90)	26.78 (21.61, 35.20)
	Max $Speed_{ML}$ (mm/s)	155.61 (33.38)	146.34 (28.62)	0.66 (0.32, 0.83)	21.96 (17.72, 28.87)
	Total $Speed_{AP}$ (mm/s)	36.58 (12.65)	32.60 (11.44)	0.64 (0.29, 0.82)	8.67 (6.99, 11.40)
	Total $Speed_{ML}$ (mm/s)	17.23 (6.50)	14.89 (5.85)	0.71* (0.42, 0.86)	3.99 (3.22, 5.24)
Double Leg Eyes Closed	$Range_{AP}$ (mm)	34.61 (9.40)	31.30 (8.55)	0.60 (0.22, 0.80)	6.66 (5.37, 8.75)
	$Range_{ML}$ (mm)	14.18 (5.77)	12.08 (4.53)	0.71* (0.41, 0.86)	3.31 (2.67, 4.35)
	$Excursion_{AP}$ (mm)	1261.62 (459.95)	1091.74 (410.59)	0.64 (0.29, 0.82)	309.44 (249.65, 406.75)
	$Excursion_{ML}$ (mm)	584.69 (240.19)	501.26 (217.90)	0.73* (0.45, 0.86)	144.66 (116.71, 190.14)
	Mean $Excursion_{AP}$ (mm)	4.20 (1.54)	4.04 (1.45)	0.51 (0.02, 0.76)	1.21 (0.98, 1.59)
	Mean $Excursion_{ML}$ (mm)	1.47 (0.65)	1.34 (0.70)	0.79* (0.59, 0.90)	0.40 (0.32, 0.52)
	SD_{AP} (mm)	5.31 (1.83)	5.03 (1.74)	0.54 (0.07, 0.77)	1.42 (1.15, 1.87)

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	SD_{ML} (mm)	1.94 (0.85)	1.73 (0.84)	0.77* (0.54, 0.88)	0.51 (0.41, 0.67)
	Area (mm^2)	204.85 (132.56)	168.11 (115.86)	0.64 (0.30, 0.82)	89.11 (71.89, 117.13)
	Max $Speed_{AP}$ (mm/s)	311.73 (62.31)	286.20 (48.01)	0.78* (0.47, 0.90)	30.22 (24.38, 39.72)
	Max $Speed_{ML}$ (mm/s)	152.04 (32.57)	144.75 (25.96)	0.80* (0.60, 0.90)	16.72 (13.49, 21.97)
	Total $Speed_{AP}$ (mm/s)	42.05 (15.33)	36.39 (13.69)	0.64 (0.29, 0.82)	10.31 (8.32, 13.56)
	Total $Speed_{ML}$ (mm/s)	19.49 (8.01)	16.71 (7.26)	0.73* (0.45, 0.86)	4.82 (3.89, 6.34)
Single Leg Eyes Opened	$Range_{AP}$ (mm)	46.59 (12.98)	43.13 (10.20)	0.58 (0.18, .079)	8.87 (7.16, 11.66)
	$Range_{ML}$ (mm)	29.03 (6.75)	27.67 (4.62)	0.53 (0.07, 0.76)	4.62 (3.73, 6.07)
	$Excursion_{AP}$ (mm)	832.23 (171.25)	822.15 (181.99)	0.81* (0.64, 0.91)	100.14 (80.79, 131.62)
	$Excursion_{ML}$ (mm)	475.01 (81.99)	462.73 (86.57)	0.83* (0.66, 0.91)	45.49 (36.70, 59.80)
	Mean $Excursion_{AP}$ (mm)	6.26 (1.70)	5.76 (1.42)	0.61 (0.23, 0.80)	1.16 (0.94, 1.52)
	Mean $Excursion_{ML}$ (mm)	4.87 (2.10)	4.52 (0.89)	0.36 (-0.28, 0.68)	1.42 (1.15, 1.87)
	SD_{AP} (mm)	8.04 (2.24)	7.38 (1.74)	0.61 (0.25, 0.80)	1.47 (1.19, 1.94)
	SD_{ML} (mm)	5.99 (2.31)	5.59 (1.07)	0.39 (-0.21, 0.70)	1.57 (1.26, 2.06)
	Area (mm^2)	919.69 (636.70)	773.81 (302.95)	0.43 (-0.12, 0.71)	423.79 (341.90, 557.05)
	Max $Speed_{AP}$ (mm/s)	401.14 (103.14)	377.46 (90.91)	0.55 (0.12, 0.77)	76.26 (61.53, 100.24)
	Max $Speed_{ML}$ (mm/s)	225.90 (32.81)	211.87 (35.93)	0.66 (0.33, 0.83)	23.57 (19.01, 30.98)
	Total $Speed_{AP}$ (mm/s)	83.22 (17.12)	82.22 (18.20)	0.81* (0.62, 0.91)	10.01 (8.08, 13.16)
	Total $Speed_{ML}$ (mm/s)	47.50 (8.20)	46.27 (8.66)	0.82* (0.66, 0.91)	4.55 (3.67, 5.98)
Single Leg Eyes Closed	$Range_{AP}$ (mm)	63.40 (13.94)	59.19 (13.62)	0.14 (-0.69, 0.57)	13.24 (10.69, 17.41)
	$Range_{ML}$ (mm)	41.70 (5.21)	39.06 (4.40)	0.47 (-0.10, 0.73)	3.91 (3.15, 5.14)
	$Excursion_{AP}$ (mm)	1013.34 (163.27)	971.85 (171.41)	0.87* (0.73, 0.94)	77.30 (62.36, 101.61)
	$Excursion_{ML}$ (mm)	674.43 (110.46)	641.57 (95.56)	0.80* (0.59, 0.90)	56.57 (45.64, 74.35)

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Mean Excursion$_{AP}$ (mm)	9.22 (1.83)	8.61 (1.87)	0.12 (-0.71, 0.56)	1.78 (1.44, 2.35)
Mean Excursion$_{ML}$ (mm)	8.09 (1.33)	7.40 (1.08)	0.48 (0.01, 0.73)	0.97 (0.78, 1.27)
SD$_{AP}$ (mm)	11.69 (2.31)	10.97 (2.36)	0.09 (-0.79, 0.54)	2.28 (1.84, 3.00)
SD$_{ML}$ (mm)	9.73 (1.51)	8.91 (1.24)	0.45 (-0.03, 0.72)	1.12 (0.91, 1.48)
Area (mm^2)	2146.74 (691.06)	1856.80 (639.35)	0.22 (-0.46, 0.60)	619.15 (499.51, 813.83)
Max Speed$_{AP}$ (mm/s)	471.20 (151.87)	454.46 (139.87)	0.29 (-0.45, 0.65)	133.44 (107.66, 175.40)
Max Speed$_{ML}$ (mm/s)	334.07 (86.04)	304.29 (52.59)	0.42 (-0.10, 0.70)	60.36 (48.70, 79.34)
Total Speed$_{AP}$ (mm/s)	101.33 (16.33)	97.19 (17.14)	0.87* (0.73, 0.94)	7.73 (6.24, 10.16)
Total Speed$_{ML}$ (mm/s)	67.44 (11.05)	64.16 (9.56)	0.80* (0.59, 0.90)	5.66 (4.56, 7.44)

SD, standard deviation; ICC, intraclass correlation coefficient model (2, k); SEM, standard error of measurement; CI, confidence interval

*Acceptable test-retest reliability (ICC≥0.70)

Robbins SM, Caplan RM, Aponte DI, St-Onge N (2017). Test-retest reliability of a balance testing protocol with external perturbations in healthy adults. Gait & Posture, 58, 433-439. doi: 10.1016/j.gaitpost.2017.09.007.

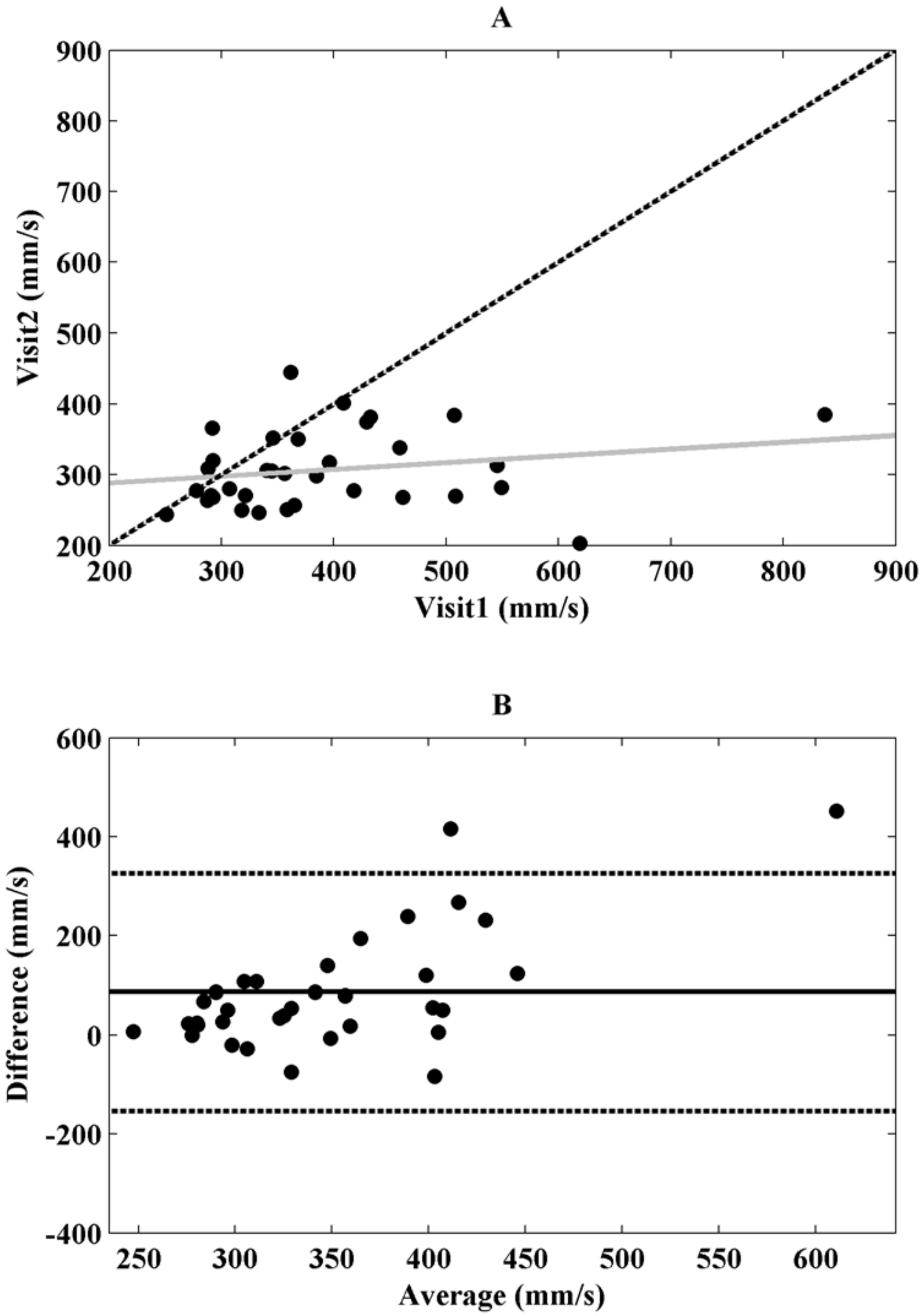

Figure 1. Scatter plot (A) and Bland-Altman plot (B) for Max Speed$_{AP}$ during the double leg stance with posterior perturbation condition. The solid, grey line in the scatter plot (A) represents the line of best fit and the dashed, black line represents the identity line (y=x). For the Bland-Altman plot (B), the differences between visits (visit 1 – visit 2) is plotted against the average of the visits. For this plot, the solid line represents the mean difference between visits and dashed lines represent limits of agreement (i.e. two standard deviations from the mean difference line). An outlier is represented by the data point on the far right side of the horizontal axis.

Robbins SM, Caplan RM, Aponte DI, St-Onge N (2017). Test-retest reliability of a balance testing protocol with external perturbations in healthy adults. Gait & Posture, 58, 433-439. doi: 10.1016/j.gaitpost.2017.09.007.