Agreement between measurements of stance width using motion capture and center of pressure in individuals with and without Parkinson's disease

J. Lucas McKay, Ph.D., M.S.C.R.

The Wallace H. Coulter Department of Biomedical Engineering, Emory University and the Georgia Institute of Technology

Research Article
Submitted to
PLoS ONE

Correspondence to: J. Lucas McKay, Ph.D., M.S.C.R.
Wallace H. Coulter Department of Biomedical Engineering
Emory University and the Georgia Institute of Technology
Room R154
Emory Rehabilitation Hospital
1441 Clifton Road
Atlanta, Georgia, 30322
USA
j.lucas.mckay@emory.edu

Word count (Abstract): 245
Word count (Main text): 1302
Figures and Tables: 2
References: 19

Running title: Stance width estimation from kinematic and kinetic data

Conflict of interest statement: The author has no conflicts of interest to declare.

Abstract

Background

Many individuals with Parkinson's disease exhibit narrow stance width during balance and gait. Because of this, stance width is an important biomechanical variable in many studies. Measuring stance width accurately using kinematic markers in parkinsonian patients can be problematic due to occlusions by research staff who must closely guard patients to prevent falls.

Methods

We investigated whether a measure of stance width based on the mediolateral distance between the center of pressure under each foot could approximate stance width measured with kinematic data. We assessed the agreement between estimates of stance width obtained from simultaneous kinematic and center of pressure measures during quiet standing in 15 individuals (n=9 parkinsonian, n=6 age-similar neurotypical). The source data (1363 unique trials) contained observations of stance width varying between 75–384 mm (≈ 25-150% of hip width).

Findings

Stance width estimates using the two measures were strongly correlated (r = 0.98). Center of pressure estimates of stance width were 48 mm wider on average than kinematic measures, and did not vary across study groups ($F_{2,12}$=1.81, P<0.21). The expected range of differences between the center of pressure and kinematic methods was 14–83 mm. Agreement increased as stance width increased (P<0.02).

Interpretation

It is appropriate to define stance width based on center of pressure when it is convenient to do so in studies of individuals with and without Parkinson's disease. When comparing results across studies with the two methodologies, it is reasonable to assume a bias of 48 mm.

Keywords

Postural control; Center of pressure location; Measurement; Methodology; Foot position

1. Introduction

Many individuals with Parkinson's disease (PD) exhibit narrow stance width during balance and gait (1). Clinically, "narrow stance" is a postural abnormality in which the feet are placed substantially medial to the anterior superior iliac spines (ASIS) (2). Stance width is therefore an important variable in many studies of parkinsonian posture and balance (e.g., (3-5)). It is typically treated as a nominal single value or as a range of values described by the mediolateral distance between kinematic markers placed on the heels, or between the medial malleoli (3-5).

Due to repeated protective steps, dyskinesias, and other practical concerns when studying parkinsonian balance, it is difficult to control stance width precisely during experiments – and so ideally, stance width should be measured as a continuous covariate throughout an experiment. However, doing so with kinematic markers can be problematic due to occlusions by research staff who must carefully guard patients to prevent falls.

Here, we investigated whether a proxy measure of stance width based on the mediolateral distance between the centers of pressure (CoP) beneath each foot could approximate stance width measured kinematically. As typically defined (6), the CoP is the point location of the vertical ground reaction force vector beneath the entire body, and represents a weighted average of all the pressures over the surface area in contact with the ground (6). Whole-body CoP location is often calculated as an important outcome variable in clinical balance studies (5, 7, 8). If bilateral force plates are used, CoP can be calculated separately for each foot (e.g., as it is in instrumented treadmill studies (9)). Since the CoP of each foot must be located within its boundaries, the mediolateral distance between them must be considerably associated with the stance width between the heels during bipedal standing.

We used the approach suggested by Bland and Altman (10) to assess agreement between stance width estimated from foot CoP and measured kinematically in neurotypical individuals (NT) and in parkinsonian individuals in the ON (PD-ON) (8) and OFF (PD-OFF) (11) medication states. We quantified the bias and expected range of differences associated with using stance width estimates from foot CoP rather than kinematic measures. Then, we tested whether differences between methods were

82 associated with group membership (NT vs. PD-ON vs. PD-OFF), and whether differences varied with
83 stance width (12).

84

85 ## 2. Materials and Methods

86 ### 2.1 PARTICIPANTS

87 We used baseline measurements from a convenience sample of participants in previous (3) and
88 ongoing cohort studies investigating the effects of rehabilitation on balance responses (Table 1). PD
89 participants were mild-moderate with bilateral symptoms (Hoehn and Yahr stage 2-3 (13)). All
90 participants provided written informed consent and all study procedures were approved by Institutional
91 Review Boards at the Georgia Institute of Technology and Emory University.

92 ### 2.2 EXPERIMENT

93 As in previous studies (3, 14), participants stood barefoot on two laboratory-grade force plates
94 (AMTI-OR6-6-1000, AMTI, Watertown, MA, USA). The force plates were mounted onto a custom
95 translation platform; however, analyses here considered only periods during which the platform was
96 stationary. Force and moment data were sampled at 1080 Hz and used to calculate the locations of the
97 center of pressure beneath each foot using calibration values supplied with the plates (15-17). Kinematic
98 data were collected at 120 Hz using a Vicon motion capture system (Centennial, CO, USA) and a 25-
99 marker set including reflective markers placed on the left and right heels. Average foot CoP locations and
100 heel marker positions were calculated over the first 250 ms of each trial.

101 Stance width was controlled by requesting participants press an object (typically a book) between the
102 medial surfaces of their feet, which was subsequently removed before data collection (≈87% of trials), or
103 by manipulating participant's feet so that kinematic markers on the heels were aligned in the mediolateral
104 direction with tape marks on the floor (≈13%).

2.3 DATA ANALYSIS

Stance width measurements derived from CoP and kinematic data were plotted against each other and examined visually. After visual assessment of outliers, trials were excluded due to: 1) tension in a ceiling-mounted fall arrest tether interfering with CoP calculation (17 trials in one participant), and 2) absent video records preventing trial review (2 trials in one participant). After applying exclusions, 1363 trials (41 – 161 per participant) were available for analysis. Stance widths were expressed in mm and normalized to inter-ASIS distance.

Following Bland and Altman (10), correlation between the two measurements was assessed with the Pearson product-moment correlation coefficient r. Differences between methods were calculated for each trial and averaged across trials into a single difference value d_i for each participant. Mean values across methods were calculated for each trial and averaged into a single mean value m_i for each participant. Bias between the two methods was quantified as the mean difference $\underline{d}$ (CoP – kinematic method) and the standard deviation of the differences s. The limits of agreement were calculated as the range $\underline{d}$–2s to $\underline{d}$+2s. Variation of differences d_i across groups was assessed with one-way ANOVA. Associations between differences d_i and mean values m_i were assessed with r (12). Data processing was performed in Matlab (r2016b, The Mathworks, Natick, MA, USA). Statistical procedures were performed in SAS Studio (3.5, The SAS Institute, Cary, NC, USA) and considered significant at $P = 0.05$.

3. Results

Stance widths measured from kinematic data varied between 75 – 348 mm, corresponding to 24.9 – 154.1% of inter-ASIS distance. CoP and kinematic stance width measurements are presented in Figure 1A. The two measures were strongly correlated ($r = 0.98$). The mean difference $\underline{d}$ between methods was 48 mm, and the standard deviation of the differences (s) was 17 mm. Differences d_i did not vary across groups ($F_{2,12}=1.81$, $P<0.21$). The limits of agreement, defined as the range $\underline{d}$–2s to $\underline{d}$+2s (10), was 14–83 mm. A "Bland-Altman plot" of the differences between the two methods d_i against their means m_i is presented in Figure 1B. d_i and m_i were significantly negatively correlated ($r = –0.59$, $P<0.02$).

4. Discussion

Stance width is an important variable in many studies of parkinsonian (4, 5) and neurotypical (18, 19) posture and balance. We found that stance width estimates from foot CoP and kinematic markers were strongly linearly correlated, and that on average, measures of stance width derived from CoP were 48 mm wider than those derived from kinematic markers. This bias that can be explained by the externally-rotated "toe out" posture used by most participants, in which a substantial portion of the foot plantar surface lies lateral to the posterior face of the heel. Overall, these results suggest that foot CoP location, a commonly calculated variable in clinical biomechanics studies (5, 7, 8) can be used to approximate stance width in healthy aging and in individuals with PD in the ON and OFF medication states.

We noted that differences between methods were non-negligible – ranging from 14 to 83 mm. However, this precision is adequate to discriminate between nominal stance widths used in the literature, which are typically separated by 100 mm or more (4, 18). Due to the high precision of CoP calculation with laboratory force plates (2-5 mm (17)), the primary source of variability in differences is probably trial-to-trial variability in weight distribution, rather than instrumentation error.

There are two notable limitations to this approach. First, differences between methods were highest at the narrow stance widths preferred by PD subjects, a fact that should be considered carefully during study design. Second, because these participants were allowed to adopt a comfortable "toe out" orientation during testing, the agreement between the methods in experimental paradigms in which foot orientation is enforced (e.g., parallel (4); 20° (18)) remains to be established.

5. Conclusion

In summary, these results suggest that: 1) it is appropriate in studies of individuals with and without PD to define stance width based on CoP, and 2) when comparing results across studies with the two methods, it is reasonable to assume a bias of 48 mm.

Acknowledgements

I thank Dr. Jessica Allen, Dr. Jeffrey Bingham, Dr. Madeleine Hackney, Dr. Lena Ting, and Ms. Kimberly Lang for their expertise and assistance.

Funding

This work was supported by the National Institutes of Health (https://www.nih.gov/) grant numbers R21 HD075612, K25 HD086276, RR025008, UL1TR000454, KL2TR000455; and the Emory Udall Center. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests

The author has declared that no competing interests exist.

References

1. Park JH, Kang YJ, Horak FB. What Is Wrong with Balance in Parkinson's Disease? Journal of movement disorders. 2015;8(3):109-14.
2. Massano J, Bhatia KP. Clinical approach to Parkinson's disease: features, diagnosis, and principles of management. Cold Spring Harbor perspectives in medicine. 2012;2(6):a008870.
3. McKay J, Ting L, Hackney M. Balance, Body Motion, and Muscle Activity After High-Volume Short-Term Dance-Based Rehabilitation in Persons With Parkinson Disease: A Pilot Study. J Neurol Phys Ther. 2016;40(4):257-68.
4. Dimitrova D, Horak FB, Nutt JG. Postural Muscle Responses to Multidirectional Translations in Patients With Parkinson's Disease. J Neurophysiol. 2004;91(1):489-501.
5. Dimitrova D, Nutt J, Horak FB. Abnormal force patterns for multidirectional postural responses in patients with Parkinson's disease. Experimental Brain Research. 2004;156(2):183-95.
6. Winter DA. Human balance and posture control during standing and walking. Gait Posture. 1995;3(4):193-214.
7. Bolger D, Ting LH, Sawers A. Individuals with transtibial limb loss use interlimb force asymmetries to maintain multi-directional reactive balance control. Clin Biomech. 2014.
8. Hass CJ, Waddell DE, Wolf SL, Juncos JL, Gregor RJ. Gait initiation in older adults with postural instability. Clin Biomech. 2008;23(6):743-53.
9. Owings TM, Grabiner MD. Step width variability, but not step length variability or step time variability, discriminates gait of healthy young and older adults during treadmill locomotion. J Biomech. 2004;37(6):935-8.
10. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet. 1986;1(8476):307-10.
11. Marusiak J, Jaskolska A, Koszewicz M, Budrewicz S, Jaskolski A. Myometry revealed medication-induced decrease in resting skeletal muscle stiffness in Parkinson's disease patients. Clinical biomechanics. 2012;27(6):632-5.
12. Shoukri M, Hashim S. Analysis of Method Comparison Studies Using SAS. SAS User's Group International Proceedings; Seattle, WA, USA2003.
13. Hoehn MM, Yahr MD. Parkinsonism: onset, progression and mortality. Neurology. 1967;17(5):427-42.
14. Welch TD, Ting LH. Mechanisms of motor adaptation in reactive balance control. PloS one. 2014;9(5):e96440.
15. AMTI Inc. AMTI Biomechanics Platform Instruction Manual. Watertown, MA, USA: AMTI Inc.; 2004.
16. AMTI Inc. AMTI Force Platform Calculations. Watertown, MA, USA: AMTI Inc.; 1991.
17. Bartlett HL, Ting LH, Bingham JT. Accuracy of force and center of pressure measures of the Wii Balance Board. Gait Posture. 2014;39(1):224-8.
18. Henry SM, Fung J, Horak FB. Effect of stance width on multidirectional postural responses. J Neurophysiol. 2001;85(2):559-70.
19. Torres-Oviedo G, Ting LH. Subject-Specific Muscle Synergies in Human Balance Control Are Consistent Across Different Biomechanical Contexts. J Neurophysiol. 2010;103(6):3084-98.

Figure legends

Figure 1. Comparison of stance width measurements from kinematic and CoP data. A: Plot of results of one method (CoP, ordinate) against those of the other (kinematics, abscissa). Marker shapes designate study group and participants are coded by color. B: "Bland-Altman" (10) plot of limits of agreement between the two methods. The CoP method introduces an absolute bias $\underline{d}$ of 48 mm and an expected range of deviations 14-83 mm. Color and marker codes are as in part A.

Tables

Table 1. Demographic, clinical, and anthropometric features of the study population.

Participant	Hoehn & Yahr Stage	Age	Sex	Height, m	Weight, kg	Inter-ASIS distance, cm	Left leg length, cm	Right leg length, cm
Neurotypical								
NT1	-	54	F	1.62	66.7	31.3	86.5	88.5
NT2	-	56	F	1.78	74.8	24.7	98.0	98.0
NT3	-	58	M	1.64	67.2	25.5	82.5	82.0
NT4	-	64	M	1.80	95.2	22.0	91.0	91.8
NT5	-	70	F	1.57	51.0	22.3	82.0	82.0
NT6	-	77	M	1.85	81.9	27.8	106.0	105.0
PD-ON								
PDON1	2	68	M	1.80	80.9	28.5	93.5	94.0
PDON2	2	69	F	1.55	74.8	30.1	84.0	83.0
PDON3	3	73	F	1.80	62.7	21.1	90.0	91.0
PDON4	2.5	79	M	1.68	68.2	27.5	91.0	90.0
PDON5	3	79	M	1.70	74.4	24.0	89.5	90.0
PD-OFF								
PDOFF1	3	75	F	1.54	50.3	22.3	83.0	82.0
PDOFF2	2	53	M	1.75	86.2	25.1	90.4	89.7
PDOFF3	2	54	F	1.63	66.0	26.2	88.0	88.0
PDOFF4	3	82	F	1.68	59.9	25.5	94.8	94.1

Abbreviations: ASIS, anterior superior iliac spine; PD-ON, PD participants in the ON medication state; PD-OFF, PD participants after 12+ hours of withdrawal of antiparkinsonian medications.