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Short Communication

Dynamic stability margin using a marker based system and Tekscan: A comparison of four gait conditions

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ABSTRACT

Stability during gait is maintained through control of the center of mass (CoM) position and velocity in relation to the base of support (BoS). The dynamic stability margin, or the interaction of the extrapolated center of mass with the closest boundary of the BoS, can reveal possible control errors during gait. The purpose of this study was to investigate a marker based method for defining the BoS, and compare the dynamic stability margin throughout gait in comparison to a BoS defined from foot pressure sensors. The root mean squared difference between these two methodologies ranged from 0.9 cm to 3.5 cm, when walking under four conditions: plantigrade, equinus, everted, and inverted. As the stability margin approaches −35 cm prior to contralateral heel strike, there was approximately 90% agreement between the two systems at this time point. Underestimation of the marker based dynamic stability margin or overestimation of the pressure based dynamic stability margin was due to inaccuracies in defining the medial boundary of the BoS. Overall, care must be taken to ensure similar definitions of the BoS are utilized when comparing the dynamic stability margin between participants and gait conditions.

1. Introduction

Older adults and patients with gait dysfunction are at risk of falling, with reduced gait stability being a major risk factor [1,2]. Maintaining stability during ambulation is dependent on control of the center of mass (CoM) and base of support (BoS), even in the presence of small disturbances or central control errors [3,4]. As the CoM position and velocity will be displaced outside of the BoS during portions of gait, stability is possible only with proper foot placement. Using the extrapolated center of mass (XcoM) and the distance to the BoS, the ability to maintain stability can be quantified [5,6].

In order to properly assess human movement and stability, evaluating the dynamically changing BoS is of importance. While previous work has utilized a marker based BoS [7,8] no investigation has assessed the sensitivity of this measure, especially as it is of importance when quantifying the dynamic stability margin (DSM). The lateral boundary of the BoS has been approximated [9] but an accurate representation of the BoS during gait has not been assessed. Additionally, during pathological gait, among patients with forefoot equinus, forefoot valgus or forefoot varus [10] the ability to place the foot and maintain a proper BoS might be compromised. Understanding and properly defining the BoS, while using a pressure sensor on the feet as the standard, might provide a better means for assessing the DSM.

Therefore, the purpose of this study was to investigate the dynamically changing BoS and the DSM during level walking and three simulated pathological walking conditions. Specifically, the DSM during plantigrade walking, equinus walking, and walking on the lateral or medial borders of the feet were investigated using both a foot pressure sensor and markers on the feet. A comparison of DSM to the arch index was further investigated to determine any changes due to foot anthropometrics.

2. Materials and methods

2.1. Experimental design

This cohort study included 13 healthy young adults (8 Females; average (SD) age of 25.1 (2.9) years; body mass index (BMI) of 22.1 (2.1) kg/m^2), who were free of musculoskeletal deficits, neurological impairment or lower extremity surgery. All participants provided written informed consent prior to data collection. The study protocol was approved by the Mayo Clinic Institutional Review Board.

Participants were asked to walk barefoot across an 8 m walkway at a self-selected pace under four conditions: (1) plantigrade, (2) equinus, (3) inverted and (4) everted walking. Prior to each condition, a demonstration was provided to familiarize the participants with each condition. During the

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equinus, inverted, and everted conditions, subjects were asked to walk only on the forefeet, lateral border of their feet, and medial border of their feet, respectively. These three conditions were investigated in order to simulate walking with a pathology.

2.2. Data collection

Fifty-eight reflective markers were placed on bony landmarks to define a 13-segment model. Three dimensional marker trajectories were recorded using a 10 camera system (Motion Analysis Inc., Santa Rosa, CA, USA) at 120 Hz and low-pass filtered using a fourth order Butterworth filter at a cutoff frequency of 8 Hz. An F-Scan 3001E foot pressure sensor (Tekscan, Inc., Boston, MA, USA) was affixed to the underside of each foot using double-sided tape. Tekscan data were collected at 120 Hz. Tekscan sensors were calibrated in a pressure chamber, by applying a uniform pressure to all sensels prior to each data collection. Subjects began ambulating at the edge of the capture volume, with data temporally synchronized between the two systems using the first toe off instant.

Prior to dynamic trials, a wand with 4 reflective markers was used to apply load onto the pressure sensors at the proximal calcaneus and distal ends of the 1st and 5th phalanges. Using the locations of the Tekscan coordinate system in the motion coordinate system, a transformation matrix for all subsequent walking trials was determined. This provided spatial synchronization of the two systems.

The arch index was assessed for both feet of each participant. The ratio of the navicular height to foot length was calculated during weight bearing on a single limb [11]. The foot length was defined as the distance from the back of the calcaneus to the metatarsophalangeal joint.

2.3. Base of support definitions

Calculations were performed using custom MATLAB programs (MathWorks Inc., Natick, MA, USA). The boundaries of the marker BoS were defined using 6 foot markers and foot anthropometrics (Fig. 1). The medial boundaries were defined between the medial calcaneus and distal 1st metatarsal markers. The lateral boundaries were defined between the lateral calcaneus and distal 5th metatarsal markers. The anterior boundary was created using a semi-ellipsoid of the distal metatarsal markers and the anterior-most point on the foot. The posterior boundary was defined by a semi-ellipsoid formed by three calcaneus markers. During heel and toe rocker portions of gait, the anterior and posterior boundaries, respectively, of the BoS were progressed anteriorly using a sigmoid function. The Tekscan BoS was determined based on the sensels in contact with the floor during stance (Fig. 2) [12]. The boundary of these pixels was created using a convex polygon hull.

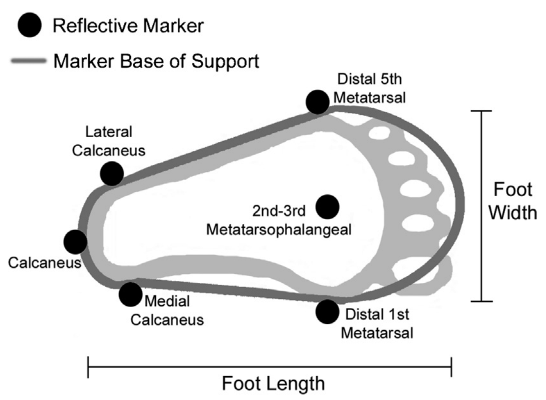

Fig. 1. Placement of foot markers and definition of the marker base of support.

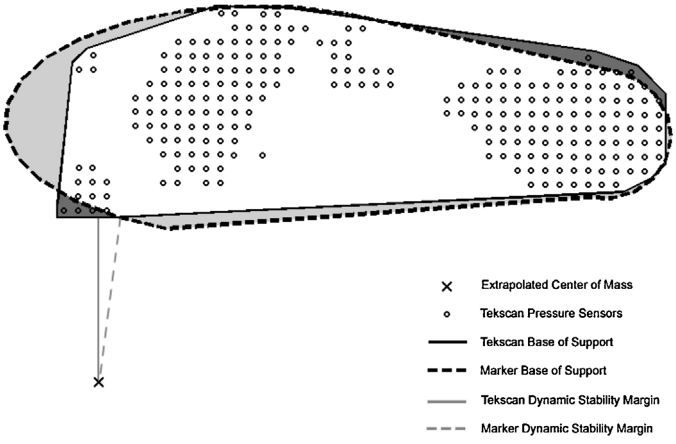

Fig. 2. Sample base of support for the foot pressure and marker based systems during midstance. The dynamic stability margin, or shortest distance from the extrapolated center of mass to the boundary of the BoS, differs based on the definition of the medial boundary.

2.4. Dynamic stability margin

The whole body CoM was calculated using the weighted sum of a 13-segment model. The XcoM was computed as:

$$XcoM = CoM + \frac{CoMv}{\omega_o}$$

where ω_o is the natural frequency ($\sqrt{g/l}$) of a non-inverted pendulum for which the COM balances on top. The length l is equivalent to 1.20–1.34 times the trochanteric height, and g is the acceleration due to gravity [5,13,14]. The CoM velocity (*CoMv*) was calculated using the Savitzky–Golay least squares method of differentiation, with the polynomial order and window length set to 5 and 11, respectively [15]. The DSM was calculated as the shortest distance from the XcoM to the BoS at each instant in the gait cycle (Fig. 2).

2.5. Data analysis

The Tekscan BoS was considered the gold standard, and the motion system BoS the test condition. While Tekscan sensors are sensitive to surface conditions, temperature and loading rates, proper calibration prior to data collection allowed for accurate measurement [16]. Differences in the DSM from the Tekscan and marker BoS were assessed using the root mean square (RMS) and average difference. Using a Shapiro–Wilk test of normalcy, the DSM was found to be non-normally distributed ($P < .001$). Therefore, non-parametric assessments were conducted. Differences in the RMS across walking conditions were evaluated using a Friedman test, with a multiple comparison post-hoc procedure performed [17]. A comparison of loaded foot arch index and DSM at contralateral heel strike during plantigrade gait was performed using a Spearman's correlation. All statistical analyses were performed in SPSS 21.0 (IBM Corp., Armonk, NY, USA).

3. Results

The marker system underestimated the DSM throughout stance, with the DSM reaching −35 cm prior to contralateral heel strike (Fig. 3A). A significant main effect of condition was demonstrated, with RMS and average differences of approximately 2.5 cm ($P < .001$; Fig. 3B and C). No differences were seen between plantigrade and equinus walking ($P = .341$), with everted walking demonstrating a reduced RMS and average difference value of approximately 0.9 cm and −0.1 cm, respectively ($P < .001$). Alternatively, inverted walking demonstrated an increased error of up to 3.5 cm ($P < .001$). No correlation was demonstrated between arch index and DSM (rho = 0.30; $P = 0.13$).

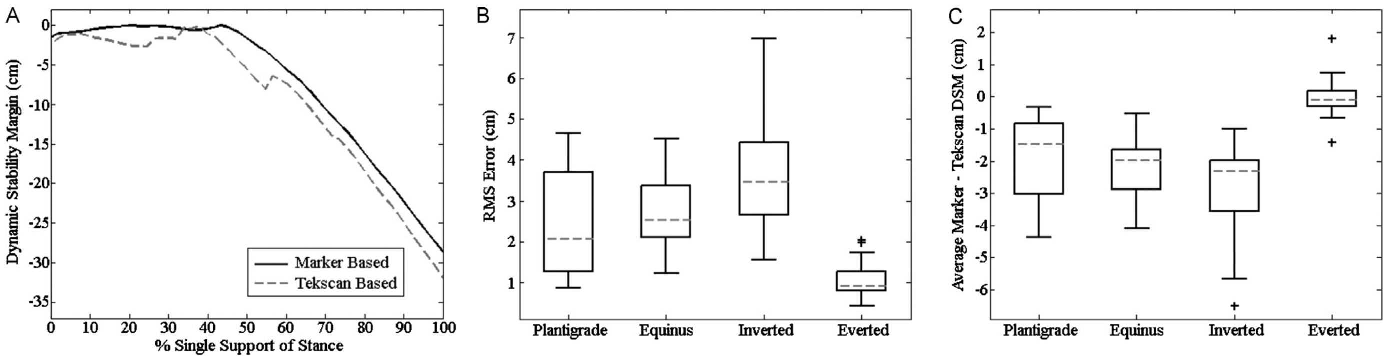

Fig. 3. The dynamic stability margin across single limb support for one representative participant (A), when utilizing the marker based BoS and the foot pressure based BoS. The dynamic stability margins demonstrated an RMS (B) between 0.9 cm and 3.5 cm during single limb support, with the marker system consistently underestimating the DSM over all conditions (C).

4. Discussion

The purpose of this study was to quantify the BoS and DSM from markers and Tekscan. Proper quantification of these values throughout gait would allow for correct identification of subjects with instability and at risk of falling [6,9].

The DSM was consistently underestimated by the marker system, or overestimated by Tekscan. During everted walking, the medial border of the Tekscan BoS increased to match that of the marker system, revealing discrepancies in the midfoot boundary for other walking conditions, although no correlations were demonstrated in comparison to participant arch height. The Tekscan system incorrectly reports loaded sensors during swing phase, and measures only vertical reaction forces, possibly altering the actual Tekscan BoS region. In the worst case scenario of inverted walking, the RMS difference demonstrated a 3.5 cm discrepancy, or approximately a 90% agreement.

The ability to quantify the BoS accurately utilizing a marker system allows for proper assessment of the DSM regardless of gait condition or presence of force plates. A marker based method for identifying the boundaries of the BoS was comparable to a Tekscan foot pressure system, with the greatest agreement occurring during everted walking. Investigators should utilize similar definitions of the BoS when comparing the DSM between participants and gait conditions.

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