THE RELATIONSHIP BETWEEN FORCE PLATFORM MEASURES AND TOTAL BODY CENTER OF MASS

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The ability of a person to maintain stable posture is essential for activities of daily living. Research in this field has evolved to include sensitive assessment technology including force platforms and 3-dimensional kinematic motion analysis systems. Although many studies have investigated postural stability under the auspice of posturography and the use of force platforms, relatively few have incorporated kinematic motion analysis techniques. Furthermore, of the studies that have utilized a multivariate research model, none have sought to identify the relationship between force platform measures including both the variation of movement of the x- and y-coordinates of the center of pressure (COP), and the 3-dimensional coordinates of the total body center of mass (COM). This study used a descriptive design to evaluate the relationship between force platform measures and the kinematic measures dealing with the total body COM in 14 healthy participants (height = 1.70 ± 0.09 m, mass = 67.7 ± 9.9 kg; age = 24.9 ± 3.8 yrs). Intraclass correlations (ICC) and standard error of measurements (SEM) were determined for common variables of interest used in standard posturography models. The results suggest that the variation of the excursion of the COP coordinates best represent the variation of the total body COM in the x- and y-directions. There was a force platform measure that correlated significantly with the vertical component of total body COM in only 3 of the 8 conditions. The ICC values obtained when analyzing individual conditions revealed that the variation in the force measurements were much more reliable than those representing the variation in movement of the

COP, suggesting a need for the development of higher order methods of modeling 3-dimensional COM information from force platforms.

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PREFACE

I would first off like to thank Dr. Joseph Myers for his indelible assistance over the course of the past 2-½ years. Your friendship, guidance, and motivation, have all significantly contributed to my personal and scholastic development over the years. I would also like to extend a special thank you to Dr. Timothy Sell, whose friendship, continual guidance, and relentless nurturing, have helped me through many tough times.

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1. INTRODUCTION

The ability of an individual to maintain postural control has been thoroughly investigated in a wide range of populations including, but not limited to, athletes (Gauffin, Tropp, & Odenrick, 1988; Pintsaar, Brynhildsen, & Tropp, 1996; Riemann, Guskiewicz, & Shields, 1999; Tropp, Ekstrand, & Gillquist, 1984), patients suffering from mild traumatic brain injury (Guskiewicz, Perrin, & Gansneder, 1996; Guskiewicz, Ross, & Marshall, 2001; McCrea et al., 2003; Mrazik et al., 2000; Riemann & Guskiewicz, 2000; Valovich McLeod et al., 2004), and in patients suffering from cerebrovascular and neurological conditions (Lafond, Corriveau, & Prince, 2004; van Wegen, van Emmerik, Wagenaar, & Ellis, 2001). These studies, for the most part, have investigated postural stability through measurement of the movement of the center of pressure (COP). A higher degree of movement of the COP has been previously used to determine an increase in postural instability (van Wegen, van Emmerik, & Riccio, 2002). Although valuable, measures of COP only relate to the clinician the movement of a 2-dimensional coordinate which represents a point of application of the total reactive forces under the individual's feet. The total body center of mass (COM), a 3-dimensional (3D) coordinate where an individual's total mass can be theoretically centered, has previously been regarded as an important variable of interest (Patla, Ishac, & Winter, 2002; Rietdyk, Patla, Winter, Ishac, & Little, 1999). Although COP and COM measurements have been recorded in previous studies, few have attempted to determine the underlying relationship between the two measurements. Those that have investigated the relationship between COP and COM have done so in the context of quiet standing (Lafond, Duarte, & Prince, 2004; Winter, Patla, Ishac, & Gage, 2003; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998).

While most studies have used two-legged stance, activities of daily living are often better replicated by more challenging tasks and different surface conditions. In orthopedic settings, it is often beneficial to perform single-leg assessments to allow for bilateral comparisons within subjects (Riemann et al., 1999). Postural instability has also been shown to increase during single-leg stance (Hasan, Lichtenstein, & Shiavi, 1990; Riemann et al., 1999). Altering the base of support can also directly influence postural control (Day, Steiger, Thompson, & Marsden, 1993; Kirby, Price, & MacLeod, 1987; Riemann et al., 1999).This is believed to occur due to the body's reorganization of the COM. For these reasons, there is a need for clinicians to be able to make inferences of the total body COM based on clinical and laboratory measures of postural stability using force platforms.

Force platforms have been used to evaluate postural steadiness in the past (Goldie, Bach, & Evans, 1989; Murray, Seireg, & Sepic, 1975). Numerous tasks have been studied such as two-legged, tandem, step, and one-legged stances (Goldie et al., 1989; Riemann & Guskiewicz, 2000). All have been shown to be increasingly difficult with foam surfaces and with the subjects' eyes closed. However, fixed and stable surfaces are the most common used in the measurement of postural stability. With force platform measurements, postural unsteadiness will be quantified by the location and variation of forces between the base of support and the support surface (i.e. force platform or foam block on platform). These variables assume a single-link inverted pendulum model of balance. Therefore, they combine COM position and acceleration (Kuo, Speers, Peterka, & Horak, 1998). The assumption of a single-link inverted pendulum model of balance in assessing postural control can be questioned. It is important, therefore, to assess postural control through the analysis of multiple variables through kinematic measurements and force platform measures; offering the advantage of assuming a multi-link inverted pendulum of balance (Kuo et al., 1998). Kuo et al. also discuss that multivariate measurements can provide information concerning the type of sway, in addition to identifying the amount of sway.

Force platform variables commonly analyzed in postural steadiness include variations in the anterior-posterior (APvar), medial-lateral (MLvar), and vertical (Vvar) ground reaction forces. Postural steadiness studies have also sought to ascertain the retest reliability of COP measures for detecting changes of postural steadiness (Goldie et al., 1989). Other measures that can be obtained from the force platform COP values include sway in the ML plane (x-direction), sway in the AP plane (y-direction), total sway, average sway velocity, and sway area.

Modeling the human body as a series of interconnected rigid links is a standard biomechanical approach (Apkarian, Naumann, & Cairns, 1989; Cappozzo, 1984). Kinematics have recently been utilized to provide an understanding of postural stability under varying conditions for different pathological populations (Brown, Shumway-Cook, & Woollacott, 1999; Henry, Fung, & Horak, 2001; Patla et al., 2002; Pozzo, Stapley, & Papaxanthis, 2002; Riemann, Myers, & Lephart, 2003; Riemann, Myers, Stone, & Lephart, 2004; Rietdyk et al., 1999; Winter et al., 2003; Winter et al., 1998). In addition to measuring the changes in postural stability of differing balance tasks with various surface conditions, kinematic analyses can be used to clarify the types of movements that occur at each limb segment (Riemann, Myers, & Lephart, 2002). Unfortunately, as studies focusing on two-legged stance begin to emerge in the literature, little research has investigated the kinematic properties associated with single-leg stances, which are a critical component of many activities of daily living. The purpose of this study was to determine what force platform measure is best able to explain the variation in the movement of the total body COM for a number of functional balance tasks. Furthermore, the reliability and precision of these force platform measures in addressing total body COM will also be investigated.

1.1. Specific Aims & Hypotheses

1.1.1. Specific Aim 1

To determine the relationship between the variability of the anterior-posterior (APvar), medial-lateral (MLvar), vertical ground reaction forces (Vvar), and the variability in the excursion of the COP in the x- (CXvar) and y-direction (CYvar), to the variability of movement measured in the total body COM as measured in the x- (COMx), y- (COMy), and z-direction (COMz).

Hypothesis 1.1: The MLvar and CXvar will both correlate highly with COMx.

Hypothesis 1.2: The APvar and CYvar will both correlate highly with COMy.

Hypothesis 1.3: The Vvar will correlate highly with COMz.

1.1.2. Specific Aim 2

To determine the reliability and precision of force platform and kinematic measures across each of the 8 testing conditions.

Hypothesis 2.1: The APvar, MLvar, Vvar, CXvar, and CYvar will be reliable and precise force platform measures.

Hypothesis 2.2: The COMx, COMy, and COMz will be reliable and precise kinematic measures for total body COM.

2. METHODS

2.1. Subjects

Fourteen participants (8 males, 6 females; height = 1.70 ± 0.09 m, mass = 67.7 ± 9.9 kg; age = 24.9 ± 3.8 yrs) volunteered for participation in the current study. All participants had no history of head injury or vestibular disorders and were free of injury to the lower extremities for at least 6 months prior to data collection. All participants read and signed an informed consent form which had been approved by the University of Pittsburgh Institutional Review Board.

2.2. Force platform data collection

Postural stability measures were performed on a Kistler 9286A (Kistler Instrument Corp.; Amherst, NY, U.S.A.) piezoelectric force sensor platform. The Kistler force platform was interfaced with a personal desktop computer via a 12-bit, 32-channel analog to digital (A/D) converter board (DT3010/32; Data Translation, Inc.; Marlboro, MA, U.S.A.). All data was recorded using the Peak Motus 3D Motion Analysis System Software Version 7.3 (Peak Performance Technologies, Inc.; Englewood, CO, U.S.A.). The analog force platform data was collected into Peak through the Analog Acquisition Module which is capable of synchronizing the analog data with kinematic data. Force platform data was collected at a sampling frequency of 120 Hz.

Stable-surface measures were performed directly on the force platform. Unstable-surfaced measures were carried out with Airex-Balance (Alcan Airex AG; Sins, Switzerland) low-density foam (47.5 cm x 29.5 cm x 6.0 cm, density = 86.04 kilograms per cubic meter) placed directly on the force platform. To minimize any electronic drifts, the force platform was allowed temperature stability for 45 minutes prior to data acquisition and data offsets were taken prior to each trial.

2.3. Kinematic data collection

Three-dimensional (3D) motion data from 29 retroreflective markers during the balance tasks were collected by the Peak Motus 3D Motion Analysis System (Peak Performance Technologies, Inc.; Englewood, CO, U.S.A.) using six high-speed (120 Hz) cameras (Pulnix Industrial Product Division; Sunnyvale, CA, U.S.A.). The capture volume for the balance task was approximately 2 m wide, 2 m long, and 2 m high (8 m^3). Calibration was performed according to the manufacturer's guidelines using the wand calibration method. Acceptable calibration of the wand (0.914 m) had a mean residual error of less than 0.00200 m.

2.4. Procedures

The order of procedures with respect to postural stability and kinematic remained standardized for all the subjects. The procedural order included anthropometric measurements, retroreflective marker placement, calibration of the motion analysis system, trial data collection, and data reduction.

2.4.1. Anthropometric Measurements

Anthropometric data including height and mass were collected for all the participants. Linear and circumferential measurements of the lower and upper extremity were collected prior to testing with a tape measure and used to calculate 3D kinematic data. All measurements were collected by the primary investigator. The lower extremity anthropometric measurements included thigh length, shank length, ankle height, thigh circumference, calf circumference, knee diameter, malleolar diameter, foot width, and foot length. Upper extremity anthropometric measurements included arm length, arm circumference, elbow circumference, elbow diameter, forearm length, forearm circumference, wrist diameter, hand circumference, and hand length.

Finally, these anthropometric measurements were inputted into the Peak software prior to data collection.

2.4.2. Retroreflective Marker Positioning

Retroreflective markers custom made by Peak Performance Technologies with a diameter of 0.025 meters were positioned at designated anatomical landmarks (**Figure 1**) about the head, torso, shoulder, elbow, wrist, hand, pelvis, hip, knee, ankle, and foot, utilizing a modified Helen Hayes Marker Set (Kadaba, Ramakrishnan, & Wootten, 1990; Vaughan, Davis, & O'Connor, 1999). On the lower extremity, retroreflective markers were positioned, bilaterally, on the head of the second metatarsal, lateral malleolus, calcaneus, femoral epicondyle, and anterior superior iliac spine. A retroreflective marker was also positioned on the sacrum (L5-S1 disc space). Two additional markers were attached to wands (distance of 0.09 m from the skin) and positioned, bilaterally, at the lateral side of the mid-thigh and mid-calf. On the upper extremity, retroreflective markers were positioned, bilaterally, on the dorsal surface of the wrist, lateral epicondyle, and acromion. Two additional markers were attached to wands (distance of 0.09 m from the skin) and positioned, bilaterally, at the lateral side of the mid-forearm and mid-arm. One retroreflective marker was positioned on the vertex of the head with two markers positioned bilaterally on the gonion (located at the angle of the mandible).

2.4.3. Calibration of the Motion Analysis System

The global coordinate system was determined prior to all data collection. The global coordinate system was determined by calibrating a 1 m by 1.5 m “L”-shaped frame equipped with four retroreflective markers of known distances apart in view of the six high-speed cameras. This scaled the coordinates on the video screen—image plane—to real life dimensions. It also determined the orientation of each camera in the global coordinate system. This frame calibration was performed concurrently with wand calibration. Wand calibration did a final account for the curvature of the lenses on a particular testing day and provided the control points necessary for the direct linear transformation of two-dimensional coordinates to three-dimensional coordinates.

2.4.4. Trial Data Collection

Participants were informed that the goal of each postural stability task was to remain as motionless as possible. They were also instructed to maintain the test position throughout the duration of the test and regain the test position as quickly as possible in the event his or her non-supporting foot made contact with the force platform or if they used his or her arms for balancing. Furthermore, they were instructed not to touch his or her supporting leg with the non-supporting leg in the single-leg tasks. Participants were asked to verbally signal their readiness for the start of the task. All testing was performed barefoot.

The subjects randomly performed eight balance tasks of three trials lasting 10 seconds each, with a two-legged standing rest period of 10 seconds between each testing trial. It has been found in previous studies that touchdowns, even in short testing periods, could not be totally avoided in single-leg tasks (Goldie et al., 1989). As such, trials with touchdowns on the force platform were accepted. However, trials in which the participant stepped off the force platform were rejected since it had previously been shown that the force platform is no longer measuring postural steadiness in these cases (Goldie, Evans, & Bach, 1992). Furthermore, if the subject removed his or her hands from their hips more than 3 times in one trial, the trial was rejected. The participants were tested in the following stance positions:

1. Two-legged, eyes open, on a stable surface (**Figure 2**)
2. Two-legged, eyes closed, on a stable surface (**Figure 3**)
3. Two-legged, eyes open, on a foam surface (**Figure 4**)

4. Two-legged, eyes closed, on a foam surface (**Figure 5**)
5. Step (one foot in front (not heel to toe) of the other), eyes open, on a stable surface (**Figure 6**)
6. Step, eyes closed, on a stable surface
7. Single-leg, eyes open, on a stable surface (**Figure 7**)
8. Single-leg, eyes closed, on a stable surface (**Figure 8**)

2.4.5. Data reduction

Kinematic data from the postural stability tasks were filtered with a 4th order Butterworth filter using an optimal cut-off frequency method (prescribed limit = 0.01) (Jackson, 1979). Processed kinematic data from the postural stability tasks underwent kinematic calculations within Peak Motus software's KineCalc module according to previously published methods (Vaughan et al., 1999). A 12-segment model was developed to estimate the total body COM, consisting of the feet (2), legs (2), thighs (2), forearms (2), arms (2), head/neck, and trunk. The x-, y-, and z-coordinates of the total body COM were a weighted average of the COM's of each individual segment and were calculated using the following formula

$$\mathrm{COM}(j) = \frac{1}{M}\sum_{i=1}^{12}\mathrm{COM}_i(j)\cdot m_i$$

where j is the coordinate of interest (i.e. x, y, or z), M is the total body mass, m_i is the mass of the ith segment, and $\mathrm{COM}_i(j)$ is the j coordinate of ith segment. The variability of movement of the total body COM coordinates (COMx, COMy, and COMz) were further calculated using a custom program in Matlab Version 6.0 Release 12 (The Mathworks, Inc.; Natick, MA, U.S.A.).

Variables that were collected through the Peak Motus software using the Kistler force platform included the following: anterior-posterior (AP), medial-lateral (ML), and vertical ground reaction forces (VGRF); and the x- and y-coordinates of the COP. The standard deviations of the AP, ML, and VGRF were calculated within Peak Motus software's KineCalc module and are reported in this study as APvar, MLvar, and Vvar, respectively. The variability of the COP coordinates from the force platform were further analyzed using a custom program in Matlab and are reported as CXvar and CYvar.

2.5. Statistical analysis

In order to address Specific Aim 1, pairwise correlations were employed to analyze the linear relationships between two variables. Pairwise correlations were performed with all of the outcome measures: APvar, MLvar, Vvar, CXvar, CYvar, COMx, COMy, and COMz. Pairwise correlations were performed using Intercooled Stata 7.0 (Stata Corporation; College Station, TX, U.S.A.). Intraclass correlations (ICC-equation 2,1) and standard error of measurement (SEM) were calculated to determine the reliability across each condition for the outcome measures in order to address Specific Aim 2. The ICC provided a unitless estimate of the reliability of measurement (Denegar & Ball, 1993). The SEM provided an estimate of the precision of measurement. Reliability and precision were calculated using SPSS Version 11.0 (SPSS, Inc.; Chicago, IL, U.S.A.). Statistical significance was set a priori $\alpha = 0.05$.

3. RESULTS

The purpose of this study was to analyze the relationship between force platform measures and total body COM. This was accomplished by measuring postural control under 8 different stance conditions, each intended to provide different somatosensory feedback by disrupting vision, altering the subject's base of support, and/or altering the support surface. Postural control was measured by combining force platform measures and kinematics. The information in **Table 1** provides demographic information on the 14 participants in the study and **Table 2** provides a summary of the data measurements collected for this experiment. The values listed in Table 2 are the ensemble averaged data across all 14 participants for a given condition.

Table 1. Demographic information for subjects enrolled in the study. (F = female; M = male)

Subject	Sex	Age (years)	Height (cm)	Mass (kg)
1	F	23	167	71.7
2	M	23	176	71.0
3	M	23	158	78.6
4	F	22	159	68.2
5	F	24	165	57.6
6	M	32	173	53.0
7	M	24	187	74.7
8	M	22	174	70.0
9	F	23	165	52.3
10	M	33	174	79.4
11	M	30	182	80.0
12	M	23	168	74.7
13	F	23	172	60.0
14	F	23	160	56.4
Mean ± SD		24.9 ± 3.8	1.70 ± 0.09	67.7 ± 9.9

Table 2. Summary of results for all measurements across 8 conditions (Mean ± SD)

Condition	Apvar	Mlvar	Vvar	COPx	COPy	COMx	COMy	COMz
1	0.57 ± .20	0.73 ± .33	0.75 ± .23	3.39 ± .89	1.24 ± .32	3.34 ± .96	1.35 ± .52	0.41 ± .21
2	0.66 ± .27	0.99 ± .40	0.71 ± .26	4.33 ± 1.14	1.48 ± .36	4.14 ± 1.23	1.65 ± .49	0.51 ± .23
3	1.14 ± .58	1.52 ± .69	3.59 ± .1.88	6.02 ± 1.49	3.16 ± .76	5.00 ± 1.46	3.47 ± .71	0.66 ± .23
4	2.26 ± .90	3.92 ± 1.56	9.82 ± 6.33	13.1 ± 3.20	5.76 ± 1.40	10.00 ± 4.16	5.99 ± 2.77	2.25 ± 3.86
5	1.06 ± .32	1.07 ± .37	0.89 ± .25	3.14 ± .80	2.67 ± .56	3.18 ± 1.05	3.3 ± .85	0.44 ± .11
6	1.67 ± .40	1.53 ± .46	1.06 ± .29	4.24 ± .66	4.28 ± .90	3.82 ± .84	5.08 ± 1.45	0.49 ± .17
7	3.13 ± 1.38	2.44 ± .94	4.58 ± 1.97	6.33 ± 1.18	4.57 ± 1.13	4.90 ± 1.44	5.09 ± 1.50	1.32 ± .51
8	6.87 ± 2.56	4.88 ± 1.87	10.79 ± 5.22	12.5 ± 3.35	10.1 ± 3.21	9.26 ± 2.25	13.00 ± 4.13	2.52 ± 1.16

Note: CXvar, CYvar, COMx, COMy, and COMz, data were multiplied by a factor of 1000 for ease of presentation

3.1. Linear Relationships between Force Platform Measures and Total Body COM Components

Pairwise correlations were performed on all of the outcome measures. These correlations were performed within each balance condition. The force platform measures that most significantly correlated to the variation in movement of the individual total body COM component (COMx, COMy, or COMz) are presented in **Table 3**.

Table 3. Force platform measures best representing variation in total body center of mass (Correlation; level of significance)

Condition	COMx	COMy	COMz
1	CXvar (.877; .001)	CYvar (.905; .001)	Vvar (.781; .001)
2	CXvar (.896; .001)	CYvar (.729; .003)	N/S
3	CXvar (.848; .001)	CYvar (.745; .002)	N/S
4	CXvar (.831; .001)	CYvar (.687; .007)	CXxvar (.686; .007)
5	CXvar (.666; .009)	CYvar (.800; .001)	N/S
6	CXvar (.563; .036)	CYvar (.883; .001)	N/S
7	CXvar (.731; .003)	CYvar (.625; .017)	N/S
8	CXvar (.627; .017)	CYvar (.799; .001)	Vvar (.757; .002)

Note: N/S = No significant correlations between force platform measures and COMz

3.2. Reliability and Precision of Force Platform Measures

Intraclass correlations (ICC) and standard error of measurement (SEM) were carried out on the data to assess the reliability and precision, respectively, of force platform and kinematic variables. **Table 4** provides a summary for all the ICC and SEM values that were computed across each condition.

Table 4. Reliability (ICC) and precision (SEM) for all variables across all 8 tasks

Variable	Condition 1		Condition 2		Condition 3		Condition 4		Condition 5		Condition 6		Condition 7		Condition 8	
	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM	ICC	SEM
AP var	0.57	0.15	0.70	0.158	0.73	0.332	0.50	0.767	0.71	0.191	0.39	0.394	0.72	0.789	0.70	1.546
ML var	0.79	0.16	0.85	0.158	0.68	0.435	0.70	0.951	0.79	0.181	0.64	0.311	0.90	0.302	0.69	1.152
Vvar	0.01	0.393	0.60	0.188	0.78	0.924	0.66	4.127	0.45	0.227	0.67	0.186	0.84	0.813	0.61	3.745
CX var	0.11	0.00132	0.38	0.00117	0.27	0.00177	0.43	0.003011	0.28	0.000938	0.01	0.00112	0.28	0.00137	0.38	0.00339
CY var	0.42	0.000309	0.31	0.000391	0.37	0.000782	0.29	0.00163	0.26	0.000657	0.40	0.000884	0.15	0.00158	0.38	0.003261
COMx	0.44	0.00115	0.20	0.00166	0.30	0.00165	0.25	0.00507	0.32	0.00117	-0.11	0.0017	0.27	0.0017	0.11	0.00331
COMy	0.15	0.000595	0.21	0.000618	-0.10	0.0014	0.23	0.00346	0.13	0.00122	0.41	0.00141	0.03	0.0025	0.19	0.00547
COMz	0.74	0.000142	0.31	0.000256	0.32	0.00025	0.42	0.00374	0.07	0.000175	0.53	0.000134	0.39	0.000517	0.17	0.00171

4. DISCUSSION

Postural control is important to all activities of daily living. The primary purpose of this study was to analyze the relationship between force platform measures and total body center of mass. A fundamental aspect of this study was using a multivariate approach to assessing postural control across eight different conditions of varying difficulty. Pairwise correlations performed on the data suggest that the variation of the x-coordinate (CXvar) and y-coordinate (CYvar) of the COP best reflect the movement of the total body COM in the x- and y-planes, respectively. No force platform measures were significantly correlated to the variation of the z-coordinate of the total body COM (COMz). Our assessment of the reliability of force platform measures, however, illustrated that the variation of the forces (APvar, MLvar, and Vvar) were more reliable than the CXvar and CYvar.

The first balance condition involved 2-legged support on a stable surface, and the second balance condition was 2-legged support on a stable surface with eyes closed. We found that the variation in the excursion of the COP in both x- and y-directions were the highest significantly correlated force platform measures to COMx and COMy. For condition 1, it was found that the variation in the vertical ground reaction force (Vvar) significantly correlated with COMz. Conversely, no force platform measure significantly correlated with COMz when the subject's vision was removed. This represents the difficulty in utilizing a 2-dimensional force platform coordinate system in an attempt to represent a 3D representation of the total body COM. Furthermore, both CXvar and CYvar had poor to moderate reliability across the first 2 conditions. The intraclass correlation coefficients performed across all the variables for conditions 1 and 2 rank the MLvar and APvar as the most reliable force platform measures.

These latter results support the conclusions drawn by Goldie et al. (1989) when her group studied the reliability and validity of force platform measures.

The third and fourth conditions involved 2-legged stance on a foam (unstable) surface, with condition 4 performed with the eyes closed. It was again found that the CXvar and CYvar were the force platform measures that correlated significantly with COMx and COMy, respectively. In the case of these two conditions, the ability of force platform measures to significantly correlate to the COMz was reversed. No force platform measure was able to significantly correlate with COMz when testing was performed with the eyes open. For condition 4, however, it was found that the CXvar, in addition to best representing COMx, was also significantly correlated with the COMz. This finding speculates that a 2-dimensional coordinate can be representative of the vertical dimension of total body COM. Although CXvar and CYvar were the highest significant correlates to the COM in conditions 3 and 4, their respectively reliabilities were moderate, with ICC values ranging from .27 to .43 across both conditions. These results demonstrate that the MLvar, APvar, and Vvar, remain the most reliable of the force platform measures, maintaining the work by Goldie et al. (1989). Although reliable, they are not representative of the total body COM.

Conditions 5 and 6 introduce a step task on a stable surface. This condition was chosen since it represented a common position utilized while performing activities of daily living, and it allowed for comparison to results of other studies that have been performed using this type of task. Although CXvar and CYvar again were the best representatives of COMx and COMy, we were not able to determine a force platform measure that significantly correlated with COMz for either the eyes open (condition 5) or eyes closed (condition 6) trials. Similar to conditions 1 through 4, the reproducibility of the CXvar and CYvar were poor. Once again, it was determined that the three force vector measures were the most reliable, ranging from moderate to good.

The final two conditions assessed postural stability using a single-leg task on a stable surface, with the second being performed with the participant's eyes closed. Single-leg conditions are a very important condition to assess since they represent some activities of daily living as well as providing orthopedic clinicians the ability to make side to side comparisons for unilateral conditions. Similar to the previous 6 conditions, CXvar and CYvar again were the highest significant correlates of COMx and COMy. In addition, Vvar correlated with the COMz in the single-leg eyes closed condition, with no significant correlate to COMz when the participant performed the task with the eyes closed. The reliability for CXvar and CYvar, however, would be considered poor for condition 7 (.28 and .15, respectively) and moderate (.38 for both) for condition 8. The MLvar was the most reliable force platform measure for condition 7, which corresponds to MLvar being the best predictor of postural unsteadiness for single-leg stance with the eyes open in the Goldie et al. (1989) study.

This study shows that the variation of movement of the 2-dimensional center of pressure coordinates reflects the variation of movement of the x- and y-coordinates of the total body COM. It has been postulated that measures of center of pressure (COP) are related to measurements of total body center of mass (COM) (Lafond, Duarte et al., 2004; Winter et al., 2003; Winter et al., 1998). Lafond et al. found that the zero-point-to-zero-point double integration technique could be used to determine the COP-COM variable from a force plate. Winter et al. (2003) investigated motor mechanisms of balance during quiet standing. Their results suggest a 0^{th} order system between the COM and COP. In Winter et al. (1998), they found that the COP oscillated in phase within 6ms of the COM in all trials and in both planes. Although this current study found comparable results to the Winter et al. (1998) study in this regard, we also sought to provide information regarding the relationship between force platform measures and the vertical component of the total body COM.

One of the prominent findings of this study was that the center of pressure coordinates correlated significantly with the center of mass coordinates in the x- and y-direction. It was determined through the analysis of ICC and SEM, that the variations of the three force measures (APvar, MLvar, and Vvar) were consistently the three most reproducible force measures. This would appear to support the work by Goldie et al., which determined through a series of reliability and validity studies that force measures could best predict instability with a number of different balance conditions (Goldie et al., 1989; Goldie et al., 1992). This study, however, illustrates that although these force measures are reliable, they do not represent the variation of movement of the total body COM.

The contradicting data in this study compared to previous studies demonstrates the important of continued research exploring force platform measures that may be both highly correlated to total body COM in addition to providing reproducible and reliable results. Such studies should include assessing higher order mathematical models of postural stability which may include novel variables such as elliptical sway areas, and assessing postural stability in terms of a dynamical systems model. The current study demonstrates that some force platform measures show promise in representing what is occurring at the total body COM, but continued research is necessary to determine what variables may be most accurate and reliable.

This study was limited by a relatively small sample size. Although the participants in this study were controlled for any lower extremity injuries sustained in the 6 months prior to testing and history of head injury or balance disorders, their level of physical activity was not controlled for. The purpose of this study was to establish the relationship between force platform measures and variables associated with total body center of mass movement. Although this study was carried out on healthy individuals, future research should investigate these established relationships within pathological populations. The findings of this study, although promising, require future validation with different populations to further extend its clinical applicability.

5. CONCLUSION

In conclusion, this study demonstrated a significant relationship between the variations of the excursion of the center of pressure coordinates to that of the movement of the total body center of mass for each of the 8 conditions. There were no force platform measures that were significantly correlated to the vertical component of the total body center of mass in 5 of the 8 conditions. This suggests that the 2-dimensional nature of force platforms is unable, in its basic form, to characterize a 3-dimensional coordinate representing total body center of mass. It further identified, however, that these measures were not entirely reliable; emphasizing a need to begin studying advanced mathematical models in an attempt to obtain force platform measures that both represent total body center of mass and are reliable in those measurements. Future research in this area is warranted to determine advanced models that would enable clinicians to transform basic force platform measures into variables that would provide a reliable measure to assess the 3-dimensional properties of the total body center of mass.

APPENDIX A

Figures

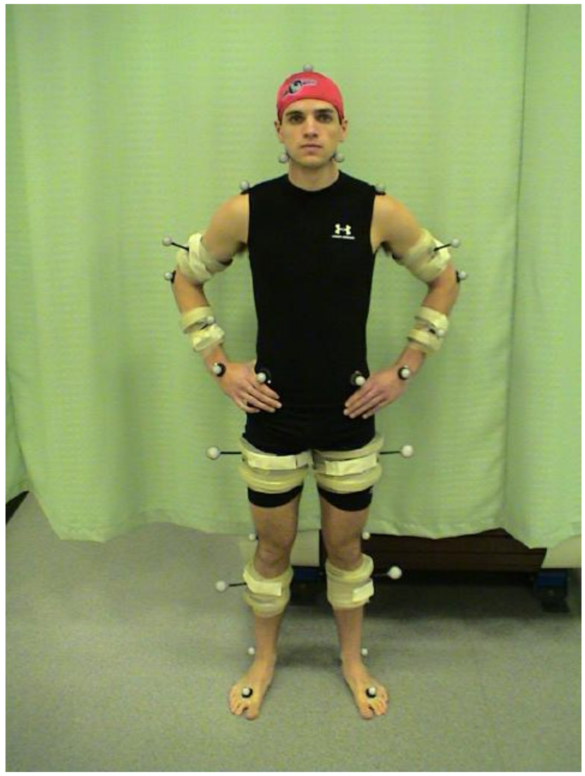

Figure 1. Retroreflective marker placement

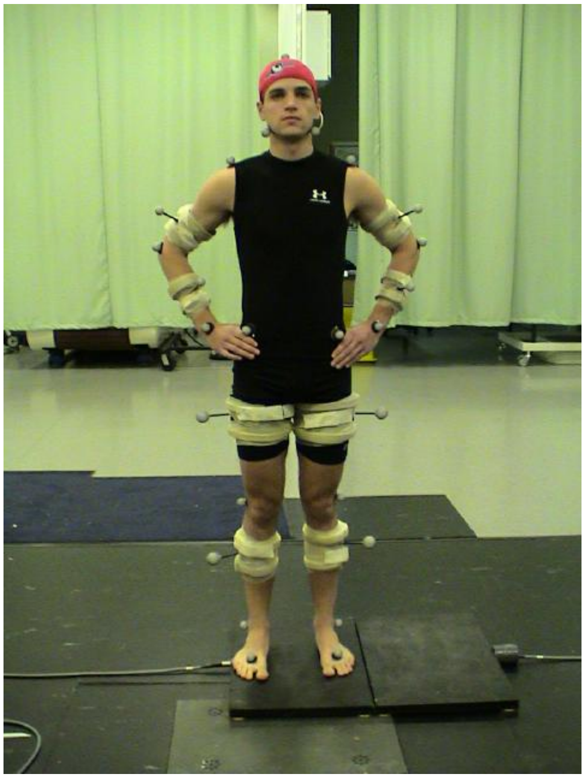

Figure 2. Two-legged, eyes open, on a stable surface

Figure 3. Two-legged, eyes closed, on a stable surface

Figure 4. Two-legged, eyes open, on a foam surface

Figure 5. Two-legged, eyes closed, on a foam surface

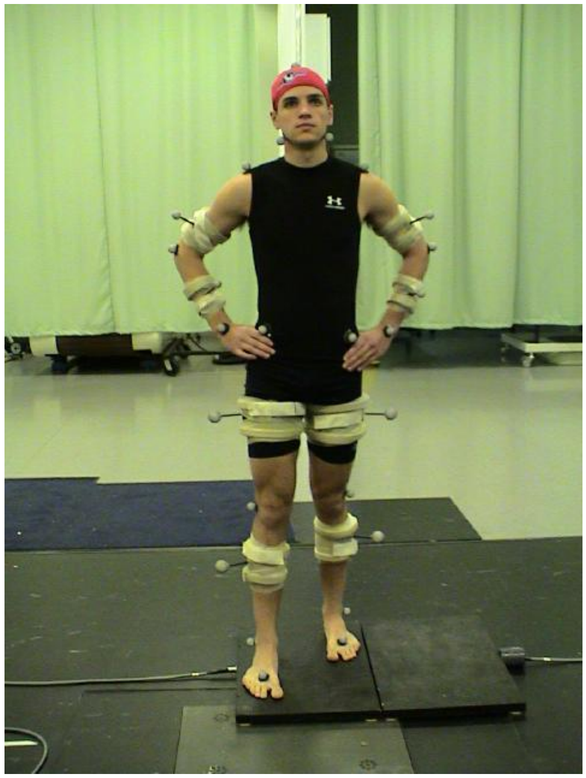

Figure 6. Step (one foot in front (not heel to toe) of the other), eyes open, on a stable surface

Figure 7. Single-leg, eyes open, on a stable surface

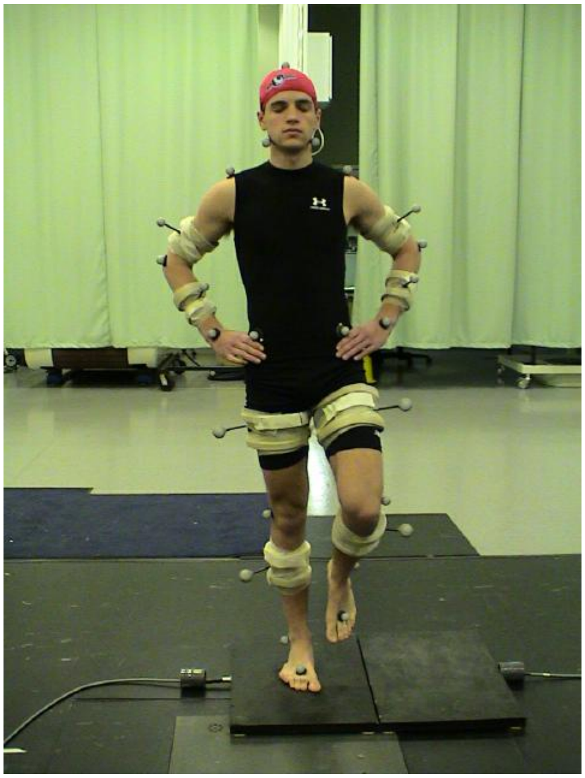

Figure 8. Single-leg, eyes closed, on a stable surface

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