Examining Methods to Estimate Static Body Sway from the Kinect V2.0 Skeletal Data: Implications for Clinical Rehabilitation

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ABSTRACT

Static body sway is a clinically relevant activity parameter, used to assess postural balance, across a wide spectrum of patient populations. We have examined static body sway using two different segmental total body center of mass (TBCM) estimation methods, the Generator of Body Data III (GEBOD) and Winter's method, using Microsoft Kinect skeletal data. Twenty subjects were recruited through an IRB study and asked to perform three trials of single leg stance with their eyes closed, with positioning based on the Balance Error Scoring System. A force plate system was used to estimate the ground truth data for comparison. Results show that both GEBOD and Winter's method performed similar in estimating anterior-posterior (AP) and medio-lateral (ML) body sway. The results also show highly correlated measurements by the two TBCM estimation methods when compared with the force plate system (mean RMSE value of 10.18 mm square in AP and 8.00 mm square in ML direction). Ordinary Least Square (OLS) linear regressions were performed to improve body sway results obtained from the two methods. Improved sway range values obtained from the simple regression method was able to reduce the estimation errors by 50% (~ 10 mm in both AP and ML body sway). The two static body sway estimation methods were found reliable for obtaining body sway. Thus, the inexpensive, portable Kinect V2.0 can be used for clinical measurements.

Author Keywords

Kinect V2.0; Total Body Center of Mass; Body Sway; Rehabilitation.

ACM Classification Keywords

G.3 Probability and Statistics: Correlation and regression analysis; J.3 Life and Medical Sciences: Health; I.2.9 Robotics: Sensors.

INTRODUCTION

Control of postural equilibrium is a complex motor skill, involving the interaction of sensorimotor processes [12]. The

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assessment of postural balance has been deemed a clinically relevant measure, used to assess rehabilitative progress, as well as predict future negative health outcomes [4,13,25]. The usage of postural balance assessments has found usefulness in populations ranging from, but not limited to pediatrics, neurology, sports medicine, orthopaedics, and geriatrics [2-6]. Specifically, recent studies have shown that when assessing those with and without a history of anterior cruciate ligament injury, significant differences in postural balance are seen and often persist between groups [19]. Multiple assessment techniques are used to determine postural balance. Advancements in technology have provided the physical therapy and sports medicine community with systems, such as force plate (FP) and 3 dimensional motion capture systems, for quantitatively assessing balance. These systems provide highly accurate methods to quantitatively assess postural control by determining steadiness and dynamic stability [21]. Most postural sway measuring systems are based on force plates. The NeuroCom Functional Limitation assessments and the BioSway system by Biodex are two frequently used force plate systems for determining postural balance [1,20,24]. In order to compare the Kinect Total Body Center of Mass (TBCM) data with the force plate Center of Pressure (COP) data, the COP time series information is converted to gravity line projections (GLP) [31]. Lafond et al. and Benda et al. [3,8] compared various methods to convert COP to GLP. Results show that the zero-point-to-zero-point double integration method provided the best results for time series conversion [8]. Force plate systems can accurately quantify postural balance using the COP measurements but are expensive and are not typically portable.

Different alternatives to these expensive systems have been developed and validated [5,9,16,22]. The inexpensive Microsoft Kinect depth sensors are amongst the most considered alternatives [2,5,6,9,16,22,28]. The Kinect comes with a software development kit that provides the capability to capture 3D joint locations of the human body. Multiple studies show the potential of the Kinect in balance and gait assessment [7,15,18,23]. Using the skeletal data obtained from the Kinect^{TM} depth sensor, the TBCM can be obtained using various segmental estimation methods [10,27]. The TBCM time series can be compared with GLP and used to quantify postural balance. Yueng et al. [29] compared the TBCM determined from the Kinect skeletal model using Dempster's anthropometry data (Winter's method) [27] with the force plate GLP measurements determined using zero-point-to-zero-point integration. They also compared Vicon results [27] to determine TBCM, considering it as the ground truth. The Vicon system is a state-of-the-art 3D marker system but not validated for its TBCM estimation using Dempster's anthropometry data. Yueng et al. did not consider The Generator of Body Data (GEBOD) dataset for the TBCM estimation, which is more recent and based on a larger population. Moreover, Yueng et al. used the older version of the Kinect^{TM} sensor and software development kit for data collection and analysis. Studies claim that the newer version of the Kinect^{TM} sensor, Kinect^{TM} v2.0, provides a more accurate skeletal model with higher stability [18,26].

The objective of the study described in this paper was to examine the two segmental TBCM estimation methods for postural balance analysis and improve the sway estimation accuracy using a simple OLS regression. Subjects were asked to perform single leg stance (SLS) based on the Balance Error Scoring System (BESS) [11]. Two segmental methods, GEBOD and Winter's method, were considered to estimate TBCM from the Kinect skeletal data and were compared with the estimated GLP data obtained from the force plates, using zero-point-to-zero-point double integration [10,27,31]. The TBCM estimations provided by the two methods were compared with the GLP estimation of force plate to compare correlations between Kinect and force plate results. A Vicon system was used with the force plate system to time-sync the force plate time series data with the Kinect time-series data.

METHODS AND EXPERIMENTS

Subjects

After providing informed consent approved by the institution's human subjects review board, 20 healthy subjects, 10 males and 10 females (average age, 24.55 ± 3.16 years; mean weight 72.23 ± 14.53 kg; and height 1.71 ± 0.1 m) were recruited for the study. Anthropometric measurements included body mass, height, inter-anterior superior iliac spine (ASIS) distance, leg length, knee width, and ankle width. All limb measurements were completed bilaterally.

Balance Task Protocol

Subjects were asked to perform a SLS with their eyes closed, with positioning based on the BESS protocol [30]. Subjects performed three SLS trials by standing on the left foot with the contralateral limb held at approximately 30-degree of hip flexion and 45-degree knee flexion. Subjects were asked to maintain stability for 20 seconds with their eyes closed and hands on their hips. Subjects faced toward the KinectTM v2.0 sensor and stood on a FP system during testing. Ten seconds of each trial, starting from the first frame, were processed.

Experimental Design

An 8 camera Vicon MX-T40S motion capture system (Vicon Motion Systems Ltd., Oxford, UK), a four AMTI Optima FP system (AMTI, Watertown, MA), and a Kinect^{TM} V2.0 sensor were used. The Vicon cameras acquired data at 100 Hz and were synchronized with the FPs, which acquired data at 1000Hz. The kinematic and FP data obtained were filtered using a Butterworth filter (cutoff frequency of 6Hz to filter Vicon trajectories and 50Hz to filter analog data from force plate) and processed using Vicon Nexus 2.5 software, utilizing the Plug-in-Gait model [31]. The Vicon Nexus software provided the COP measures from the FP data and the joint angle measures from the Vicon data. The Kinect

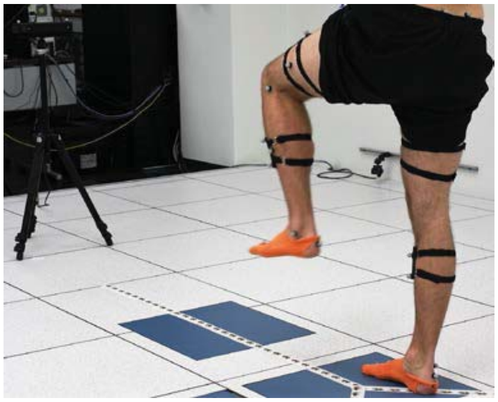

Figure 1. Subject performing a single leg stance trial in front of the Kinect (mounted on a tripod).

data were collected at a sampling rate of 30 frames per second. Finally, to match the sample rate of the Kinect, the Vicon data and FP data were re-sampled to 30 Hz using an anti-aliasing low-pass FIR filter in Fourier series using MATLAB 2015b (Mathworks Inc., MA). The Kinect data were time-synced with Vicon and FP data using hip abduction/adduction angle movement. A customized software was developed using the C# programming language and Kinect^{TM} software development kit for determining the TBCM estimations using GEBOD and Winter's method in Visual Studio 2015 (Microsoft, USA). The GLP data was estimated from the FP COP data and compared with the estimated TBCM measurements from Kinect [11, 12]. Fig. 1 shows a subject performing the single leg stance trial in front of a Kinect.

TBCM Calculation Using Segmental Method

The total body center of mass is the mean location of the distribution of all body mass segments. There are different methods for estimating TBCM. In this paper, we compare the TBCM estimated from the Kinect skeletal data using two different segmental methods with the GLP data estimated from FPs, namely, GEBOD and Winter's method [25,26].

GEBOD Method

In this method, TBCM is calculated using volume regression equations provided in GEBOD III [10]. GEBOD III has two different volume regression equation sets for males and females; it considers a 17 segment body model to measure individual segment volumes of the human body, as shown in Fig. 2. The volume regression equations considered were for the adult human male and female, which are based on human anthropometric data [17,30]. The predicting variables are weight (lb.) and standing height (in). The predicted segment volumes are in cubic inches. For the volume of each segment, a separate regression equation is given, against the predicting variables. The regression equations are multiple regression equations based on both predicting variables, generated from 46 female subjects and 31 male subjects. The total volume (TV) of the body is calculated as the sum of all segment volumes. Body density can be calculated as,

$$body\ density\ (D) = weight/TV \tag{1}$$

Assuming the body density as constant throughout the body, individual segment masses can be calculated using the formula,

$$Segment\ Mass\ =\ Segment\ Volume\ *\ D \tag{2}$$

Equation (2) calculates the individual mass of each segment. The TBCM is calculated as the weighted average of the segment masses with respect to their 3D location. Table 1 presents the 3D points selected to represent the segment centers from the Kinect skeletal model in the horizontal ground plane. The Kinect joint locations are used to determine the real-time TBCM of a person. The TBCM position of the full body is calculated as the mean of the product of segment masses and segment centers. For example, the TBCM of a human body in the X-direction is calculated as,

$$comX = \frac{\sum_{i=1}^{17} SegmentMass_i * segmentCenterX_i}{\sum_{j=1}^{17} segmentMass_j} \tag{3}$$

where comX is the x-coordinate of the TBCM of the human body and i represents each segment. Similarly, comY can be measured; these two points together constitute the TBCM on the horizontal ground plane at a particular time instant.

Winter's Method

Winter's method is a commonly used segmental approach, utilizing anthropometric data from different sources, including Dempster's data [27]. It is a more generalized 16 segment model, similar to GEBOD, with the exception of the head and neck segments being joined together, rather than two different segments. Additionally, height and weight does not play any significant role in determining the masses of segments in Winter's method. Winter's method provides the *segment mass/total body mass* ratio for all the 16 body segments [27,29]. The *center of mass/ segment length* values for each segment are also defined through regression equations. Table 2 shows the joint centers considered from the Kinect's skeletal model for Winter's model. The TBCM can be calculated as,

$$comX = \sum_{i=1}^{16} segmentMassRatio_i * segmentCenterX_i \tag{4}$$

where comX is the x-coordinate of the TBCM of the human body and *i* represents each segment. *segmentMassRatio$_i$* is the ratio of segment mass of segment *i* to the total mass. Finally, *segmentCenterX$_i$* is the TBCM position of each segment and is measured by using the CM/proximal or distal segment length ratio. The Y coordinate is calculated similarly.

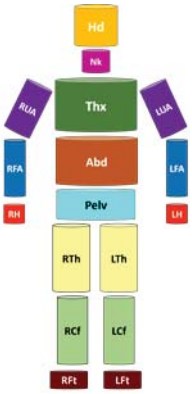

Figure 2. Body Segments for GEBOD III regression equations; Segments - Hd: Head, Nk: Neck, Thx: Thorax, Abd: Abdomen, Pelv: Pelvis, RUA and LUA: Right and Left Upper Arm, RFA and LFA: Right and Left Forearm, RH and LH: Right and Left Hand, RTh and LTh: Right and Left Thigh, RCf and LCf: Right and Left Calf, RFt and LFt: Right and Left Foot.

Body Segments	Kinect V2.0 skeletal body segment centers
Head	Head
Neck	Neck
Thorax	Mid-point between spine shoulder and spine middle
Abdomen	Mid-point between spine mid and spine base
Pelvis	Spine base
Upper arm (L/R)	Mid-point between shoulder and elbow
Forearm (L/R)	Mid-point between elbow and wrist
Foot (L/R)	Foot
Calf (L/R)	Mid-point between knee and ankle
Thigh (L/R)	Mid-point between hip and knee
Hand (L/R)	Mid-point between wrist and hand tip

Table 1. Body Segments and their assumed 3D TBCM positions for GEBOD III method.

Zero-point-to-zero-point double integration method

In the zero-point-to-zero-point double integration method, the COP determined from a FP and the vertical projection of TBCM, namely gravity line projection (GLP), are assumed to coincide when the ground reaction forces (F_H) cross the zero line. These zero-point crossings are termed as the instant equilibrium points (IEP) [11,12]. The GLP positions are estimated by double integration of the horizontal forces between each IEP that is detected by change in polarity of F_H. In this technique, the first integration constant is the initial displacement, COP(t_i) and the second integration constant is the initial velocity, v(t_i), where t_i is the i-th IEP. v(t_i) and GLP are obtained as:

$$\mathrm{v}(t_i) = \frac{COP(t_{i+1}) - COP(t_i) - \sum_{t_i}^{t_{i+1}} \Delta_t \sum_{t_i}^{t_{i+1}} \frac{F_H(t)}{M} \Delta_t}{(t_{i+1} - t_i)} \qquad (5)$$

$$\mathrm{GLP} = COP(t_i) - \mathrm{v}(t_i)(t_{i+1} - t_i) + \sum_{t_i}^{t_{i+1}} \Delta_t \sum_{t_i}^{t_{i+1}} \frac{F_H(t)}{M} \Delta_t \qquad (6)$$

where t_i and t_{i+1} are two successive instances where F_H is zero and Δ_t is the time interval between them.

RESULTS

The AP and ML sway range disagreements (SRD) are presented in Tables 3, 4 and 5, 6. To compare outcomes using the two segmental methods in measuring AP and ML postural sway, sway trials were divided into five different sway zones based on the degree of sway measurements obtained from the FP. The mean (μ) and standard deviation (σ) measures for AP and ML range disagreements for the trials in each sway zone were measured separately and all together as well. The disagreements for both AP and ML sway were comparatively lower in the mid-sway ranges (20-50mm). This gives an interesting insight about how the performance of the two Kinect models change based on the amount of sway observed in the SLS task. The performance of both algorithms were almost equivalent for all the different ranges. To improve the performance of the two methods, we considered a simple regression model and trained the instances using an OLS regression.

Body Segments	Kinect V2.0 skeletal body segment centers
C7-T1	Spine shoulder
Ear-canal	Head
T12-L1 and diaphragm	Spine mid
L4-L5	Spine base
Greater trochanter (Left/Right)	Hip
Femoral condyles (Left/Right)	Knee
Medial Malleolus (Left/Right)	Ankle
Head metatarsal II (Left/Right)	Foot
Glenohumeral axis (Left/Right)	Shoulder
Elbow axis (Left/Right)	Elbow
Ulnar styloid (Left/Right)	Wrist

Table 2. Body Segments and their assumed 3D TBCM positions for Winter's method.

Sway Range from Force Plate (mm)	Sway Range Disagreement (mm)			
	GEBOD		Winter	
	μ	*σ*	*μ*	*σ*
00-20	7.79	3.80	11.50	4.61
20-30	16.69	8.77	19.71	7.08
30-40	16.42	6.81	20.69	4.09
40-50	19.83	6.23	29.78	2.45
50-above	33.24	14.77	34.78	12.71
All Ranges	21.15	14.01	24.67	12.20

Table 3. AP Sway Range Disagreements for GEBOD and Winter's method

Sway Range from Force Plate (mm)	Sway Range Disagreement (mm)			
	GEBOD		Winter	
	μ	σ	μ	σ
00-20	11.49	3.92	11.75	5.78
20-30	8.68	4.60	5.74	5.81
30-40	7.19	4.47	4.80	2.23
40-50	4.85	4.94	6.20	2.63
50-above	14.87	14.00	13.47	14.05
All Ranges	10.67	9.70	9.34	9.84
	Regression Parameters			
R*R	0.66		0.70	
Coefficient	1.10		1.07	
Intercept	1.75		2.17	

Table 4. AP Sway Range Disagreements for GEBOD and Winter's method after OLS Regression with Regression Parameters

Sway Range from Force Plate (mm)	Sway Range Disagreement (mm)			
	GEBOD		Winter	
	μ	σ	μ	σ
0-20	9.73	4.52	9.82	5.14
20-30	10.10	4.22	11.33	3.89
30-40	12.56	5.82	13.25	6.26
40-50	21.07	6.21	21.16	5.37
50-above	23.92	7.03	20.86	7.81
All Ranges	15.91	7.96	15.98	7.30

Table 5. ML Sway Range Disagreements for GEBOD and Winter's method

Sway Range from Force Plate (mm)	Sway Range Disagreement (mm)			
	GEBOD		Winter	
	μ	σ	μ	σ
0-20	11.96	4.87	11.11	5.13
20-30	8.85	4.74	7.79	4.97
30-40	3.30	2.20	2.97	2.82
40-50	7.91	5.08	7.91	5.29
50-above	13.96	4.84	11.46	5.33
All Ranges	8.08	5.57	7.31	5.50
	Regression Parameters			
R*R	0.29		0.38	
Coefficient	0.54		0.60	
Intercept	2.44		2.34	

Table 6. ML Sway Range Disagreements for GEBOD and Winter's method after OLS Regression with Regression Parameters

The R*R values observed were high in case of AP sway range regression, with values 0.66 and .70 for the GEBOD and Winter's methods, respectively. However, the R*R values were considerably lower for the ML sway range regression, with values 0.29 and 0.38, for the two methods. In both cases the sway range disagreement was significantly improved. The mean AP SRD was improved by 10.48 mm for GEBOD, and 15.33 mm for Winter's method. Similarly, in case of ML sway range disagreement measures, the mean SRD was improved by 7.83 mm and 8.67 mm for the two methods.

The mean square disagreements for both the methods (Table 7) show that the performance was similar with an average error of 10.18 mm in AP and 8.00 mm in ML direction. To study reliability of the sway measurements, the absolute reliability for FP, Kinect with GEBOD, and Kinect with Winter's data were evaluated using Coefficient of Variation (CV). Table 8 and Table 9 show the CV values for the AP and ML sway measures, before and after the regressions were performed, respectively.

DISCUSSION

The primary objective of this study was to examine static sway measurements obtained from two different segmental TBCM estimation methods, GEBOD and Winter's method. Results from both methods were compared with the TBCM estimated from a gold standard sway assessment equipment (FP), to analyze and understand the performance of the two methods. Twenty subjects were asked to perform SLS with a portion of BESS test instructions.

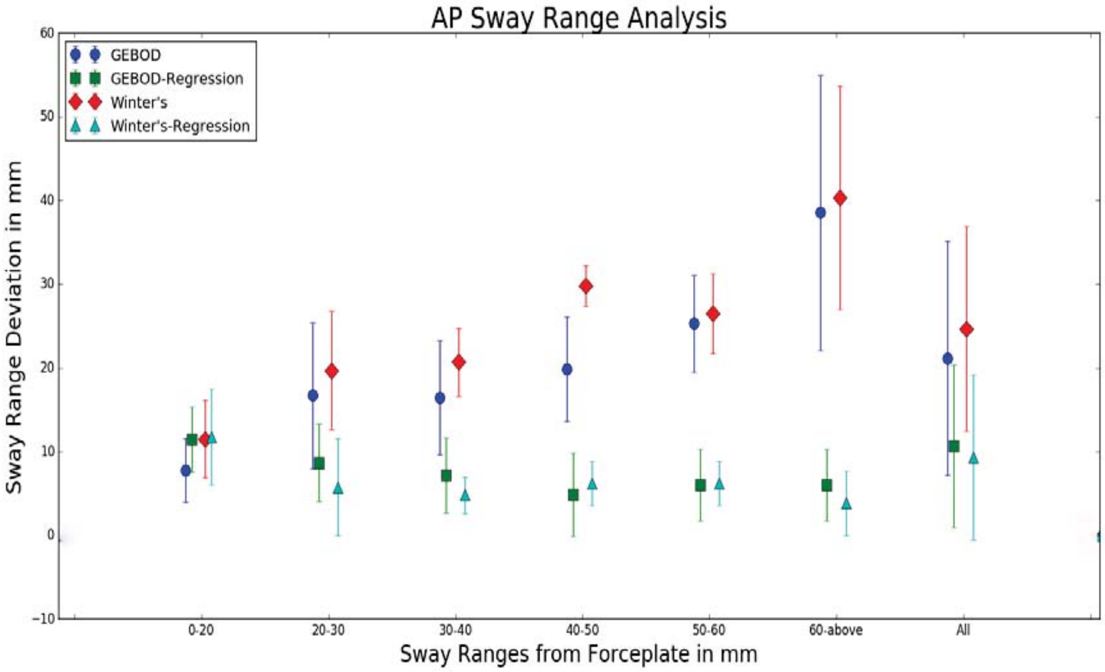

Figure 3 Anterior-posterior sway range disagreements for different force plate sway ranges.

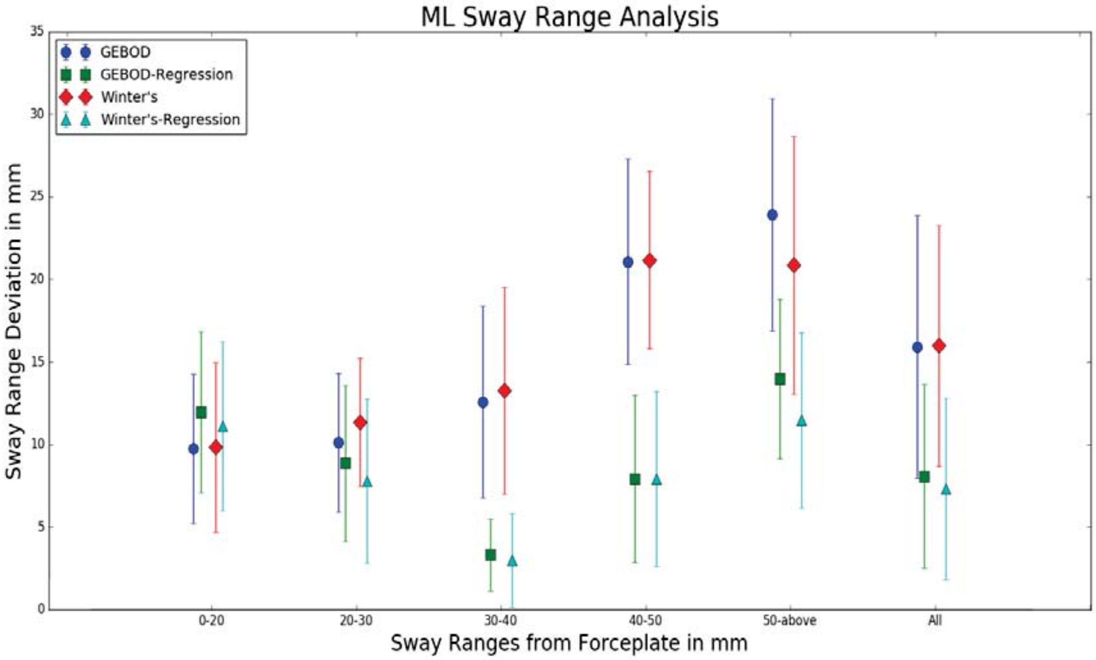

Figure 4. Medio-lateral sway range disagreements for different force plate sway ranges.

Sway Direction	MS Disagreement (mm square)			
	GEBOD		Winter	
	μ	σ	μ	σ
AP	10.07	7.91	10.29	7.50
ML	8.09	4.65	7.92	4.56

Table 7. Sway MS Disagreement for GEBOD and Winter's method

Sway Direction	CV (%)		
	FP	GEBOD	Winter
AP	45.94	55.42	64.41
ML	31.25	49.16	52.01

Table 8. CV for FP, K-GEBOD and K-Winter's Sway Measures before Regression

Sway Direction	CV (%)		
	FP	GEBOD	Winter
AP	45.94	37.44	38.51
ML	31.25	16.91	19.38

Table 9. CV for FP, K-GEBOD and K-Winter's Sway Measures after Regression

A SLS eyes closed BESS position was chosen to effectively challenge younger individuals, allowing investigators the ability to detect measurable sway differences. Sway measurements obtained using both the methods were comparable to the FP measurements with reasonable reliability. The majority of the trials had a lower to medium amount of sway of 0 – 50 mm in AP and ML. We observed comparatively higher AP sway than ML sway among the trials. Typically, during the SLS tests, most participants were observed to maintain their balance by leaning forwards, leading to more anterior sway and a higher AP range. The performance of the two methods were not significantly different in the AP and ML direction.

We could find very few observations with very high postural sway; both methods performed less efficiently in those cases with higher amount of disagreements with FP measurements. It is important to understand that the FP system has a very high sampling rate of 1000 Hz, whereas, the Kinect system has a sampling rate of only 30 Hz. Because of a lower sampling rate, Kinect is observed to miss a number of extremities while capturing data. However, results show that both the GEBOD and Winter's method are reliable for a majority of the trials that had lower to medium postural sway. Figures 3 and 4 provide a clearer view of the improved results after regression.

The measurements obtained from regression provide better results by lowering the disagreements to about 50%. The regression method used here is OLS. The coefficient and intercepts provided in the Tables 4 and 6 could be used to obtain a better estimate of AP or ML sway measures from the measurements obtained using GEBOD or Winter's method. It is necessary to understand that these regression models would only work with the skeletal data obtained from a Kinect V2.0. The Microsoft Kinect skeletal data provides an estimation of joint centers over an individual's segmented depth image. Research studies have provided information about the inaccuracy of Kinect skeletal data [26]. Therefore, the accuracy of Kinect skeletal data is assumed to have a direct impact on the study results. This can explain the errors of postural sway estimation by both GEBOD and Winter's method as both the methods use Kinect skeletal data to estimate TBCM. Additionally, the GEBOD method considers the body density to be constant throughout the entire body, which may also add more error to the results. However, GLP data obtained from FP data is also an estimation [29,31] and not the actual TBCM.

Therefore, both the Kinect and force plate TBCM estimations have some degree of inaccuracy. The previous studies on Kinect postural sway were done using the first generation Kinect [29], whereas, in this study the Kinect V2.0 is used to obtain the skeletal data. Yeung et al. [29] used the TBCM obtained from the Vicon motion capture system as the ground truth in their study to compare Kinect and FP measures. The Vicon system uses Winter's method for TBCM estimation. However, most postural sway measuring systems used in clinical practice are based on FPs, such as the Biodex and NeuroCom systems; we consider the FPs system as the most reliable source for ground truth in our experiments. The implications for advancing the accuracy of postural sway measures within a portable motion sensor device such as the Microsoft Kinect V2.0 are significant. The inexpensive nature and portability of the Microsoft Kinect V2.0 are distinct advantages over more sophisticated VICON and FP systems. This may increase the usability for clinicians to easily capture advanced postural control measures, previously being restricted to more robust and expensive systems. The scope of clinical applicability to monitor postural control ranges from youth athletic screening to the assessment of fall risk in older adults [11,19,25]. Such advances in methodology, as seen in this study, may not only improve screening techniques but also monitor the success of intervention strategies.

The CV measures after regression shows to have improved for the AP range measures only. Therefore, the reliability of the AP sway can be improved by the regression. This method does not seem to alter the reliability of ML sway range estimations. Interestingly, Garcia-Lopes et al, found that when examining the relationship of static body sway, gait and functional outcomes in those with chronic stroke, AP sway was found to be more impaired, demonstrating a greater level of directional involvement for this population

[14]. By continued improvement of the Kinect's CV, in either the AP and/or ML directions, against the current "gold standard" force plate approach, clinicians may further enhance their clinical decision-making and rehabilitative outcomes across a large population base.

CONCLUSION

In summary, we examined Kinect V2.0 skeletal data using two different segmental TBCM estimation methods as compared to the "gold standard" FP GLP estimations. We have also generalized the Kinect GEBOD and Winter's method measurements by using a simple yet effective regression that improves the results by an average mean of 10 mm. This study provides sufficient information on how the two segmental TBCM estimation methods compare when used for body sway estimation. The body sway estimation provided using either of the methods could be used with the regression coefficients to get a more accurate static postural sway measures. We conclude that both GEBOD and Winter's method can provide static body sway measurements and are reliable for clinical interventions when used with Kinect V2.0 skeletal data.

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