A Novel Depth Image Analysis Method to Calculate the Anterior Reach of the Modified Star Excursion Balance Test

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ABSTRACT

In this paper, we present a novel method to measure the anterior (ANT) reach distance of the modified Star Excursion Balance Test (mSEBT). Using depth images obtained from the Microsoft Kinect™ V2 sensor, we compared our results against a "gold standard" marker-based Vicon motion capture system. Seven healthy subjects participated in the study and were asked to perform five ANT reach trials of mSEBT bilaterally. Intra-class correlation coefficient (ICC), standard error of measurement (SEM), and smallest detectable distance (SDD) values were calculated. The Kinect demonstrated good reliability (0.7-0.9) against the Vicon in estimating absolute ANT reach and ANT reach normalized to leg length. The ICC (2,1) measurements were 0.75, 0.81 for absolute ANT reach distances and 0.81, 0.84 for normalized ANT reach measures, for the left and right foot, respectively. The SEM and SDD values of the Kinect were similar to previously reported normalized ANT reach manual measurements at 3.65, 10.11 for the left foot and 3.98, 11.04 for the right foot, respectively. For absolute ANT reach distances, the SEM and SDD values were 3.19cm, 8.85cm and 3.75cm, 10.41cm for the left and right foot, respectively. These results show potential capabilities of the depth image analysis method to provide reasonable accuracy in measuring ANT reach performance during the mSEBT.

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INTRODUCTION

The Star Excursion Balance Test (SEBT) has demonstrated consistent reliability and validity as a dynamic test to estimate relative risk of a lower extremity injury, as well as monitor rehabilitation outcomes [1-3]. The original SEBT involved reaching in 8 directions as far as possible, extending at 45-degree increments from the center of the grid, while maintaining stance on the limb being tested [3]. Due to redundancies, the SEBT was simplified to have participants reach in the anterior (ANT), posteromedial and posterolateral directions only, being renamed to the modified SEBT (mSEBT) [3, 4]. Performance is recorded as an absolute value (in centimeters) of reach distance, as well as a percentage of reach distance normalized to leg length [4]. Although percentage and absolute reach distance in all three reach directions have demonstrated clinical utility to estimate injury risk and rehab outcomes, asymmetries in the ANT direction between limbs has consistently shown the greatest predictive value [3-6]. Specifically, individuals with limb asymmetries of ≥ 4cm were 2.5 times more likely to sustain a musculoskeletal lower extremity injury [3, 6]. Unfortunately, traditional estimations of ANT reach distance are taken manually by therapists, often being time consuming and at risk for reliability errors [4, 7]. In this study, we investigate depth images of the Microsoft Kinect V2 for estimating the ANT reach of the mSEBT, further enhancing its' clinical efficiency and reliability.

There is prior work utilizing the Kinect to determine mSEBT reach distances [5]. The results obtained by Moataz et al. are promising but their methodology unfortunately involves manual identification of the toe landmark by visual inspection of the depth point cloud [5]. Manual identification of the toe landmark is time consuming and requires special technical skills. We believe that by further investigation, the ANT reach measurement can be automated without the use of human input; findings may offer an important step to increase the reliability, efficiency, and utility of marker-less motion capture in the clinical setting.

In this paper, we present a novel method to measure ANT reach distances using depth image analysis of mSEBT trials as compared to a "gold standard" Vicon motion analysis system. We hypothesize that the Kinect will demonstrate good reliability in estimating absolute ANT reach distance and normalized ANT reach distance, as compared to a Vicon motion capture system. We also hypothesize that a customized software will demonstrate similar normalized anterior reach distance standard error of measurement (SEM) and smallest detectable distance (SDD) as compared to previously reported manual methods. We include a description of the methods along with experiments and results.

METHODS AND EXPERIMENTS

Subjects

To evaluate the depth image-based algorithm estimating ANT reach distances, 9 healthy participants, 5 males and 4 females (mean age, 30.44 ± 9.29 years; mean weight 67.94 ± 6.97 kg; and mean height 174.49 ± 5.89 cm) were recruited to take part in an IRB-approved human subjects study. Anthropometric measurements included left and right leg lengths (mean left leg length 90.56 ± 4.35 cm; and mean right leg length 90.48 ± 4.39 cm) to estimate reach distance as a percentage of leg length (excursion distance/leg length × 100) [3,7,8]. Leg length was manually measured from the most inferior aspect of the anterior superior iliac spine (ASIS) to the most distal tip of the medial malleolus with the patient in supine [6]. Data from 2 out of the 9 subjects were not considered in the result analysis because of inconsistent depth camera positioning.

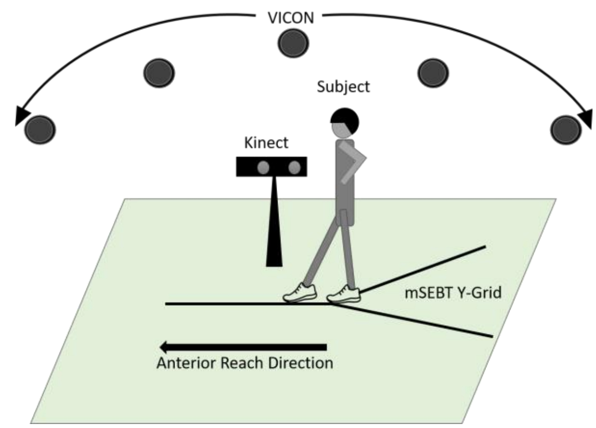

Figure 1. Setup for mSEBT data collection.

Modified Star Excursion Balance Test Protocol

The testing protocol was informed by previous investigations from Plisky et al., Clagg et al. and Hertel [3, 8, 9]. Participants, while wearing athletic shoes, were instructed to stand in single-limb stance on the test limb with the most distal aspect of their great toe at the center of the mSEBT grid. During the test, participants placed their hands at the hip and were asked to reach as far as possible with the free limb in the ANT reach direction in relation to the stance foot. Following each reach, the subject returned the reaching limb to assume a double leg stance prior to repeating the motion. The maximal reach distance was measured simultaneously by a Kinect depth camera and the Vicon motion capture system. Five trials were performed for each limb. Both absolute and percentage ANT reach distances were measured for the analysis.

Experimental Design

A 7 camera Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, UK), and Kinect^{TM} V2.0 (Microsoft Corp., Redmond, WA) were used for a time-synced data collection. The Vicon data were filtered using a Butterworth filter (cutoff frequency of 6Hz to filter Vicon trajectories) and processed using Vicon Nexus 1.8 software. Two markers were placed at the toe region of each shoe. These two markers were used to obtain the ANT reach distances from the Vicon data.

Figure 1 shows the experimental setup of the study. A Y-grid for the mSEBT was marked on the floor per the mSEBT protocol [3, 8, 9]. The Kinect depth camera was placed in the lateral direction to obtain depth images. The Kinect was mounted on a tripod and was set at a height of 1 meter. A customized Windows application was developed using the C# programming language to obtain the depth images from the Kinect device. The depth images were then processed using a customized MATLAB (Mathworks Inc., MA) code to calculate the ANT reach distances. Similarly, the Vicon marker data were processed using another customized MATLAB code to obtain the ground truth distance measurements.

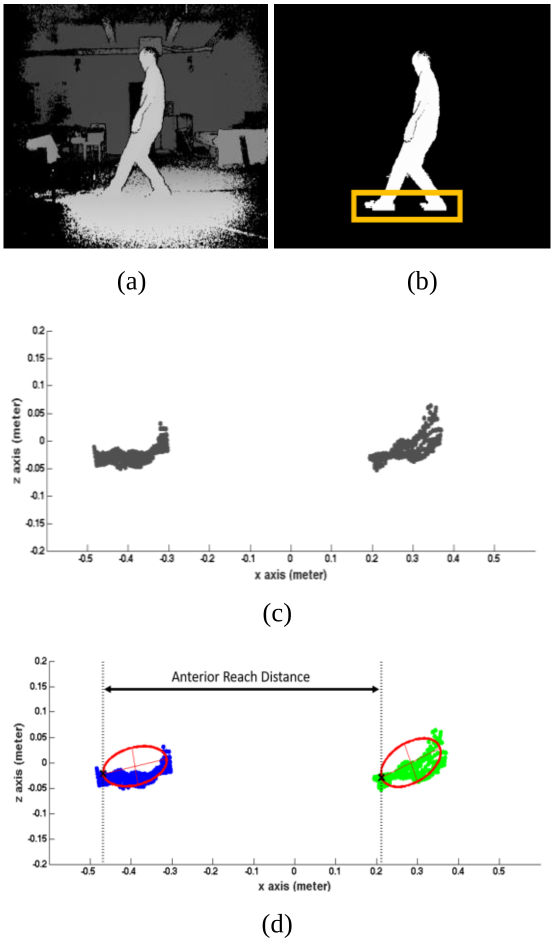

Figure 2. (a) Raw Depth Images obtained from Kinect. (b) Depth silhouette of the subject. (c) 3D point cloud projections obtained from lower foot area from the depth silhouette. (d) Point cloud projections clustered using FCM and ellipse fit.

Anterior Reach Distance Calculation

The absolute ANT reach distances were measured separately for the Kinect depth camera and Vicon. The distances between the two toe markers were used to obtain the ANT reach distances from the Vicon data. The time series toe-distance measurements were further cleaned using a moving mean filter with T = 1.5 sec. For a single trial, the maximum distance observed between the two toe markers in the filtered data was noted as the ground truth measurement for the ANT reach distance. The raw Kinect depth data were first processed using a background subtraction method to obtain the depth silhouettes of the subject as shown in Figure 2(a) and 2(b). The depth silhouettes were then processed to obtain 3D point clouds of the subject. A sample of points of the 3D point cloud with heights between 2 to 7 inches from floor plane were considered as the foot segment of the subject. The foot segment is shown in Figure 2(b), marked with a rectangular box on top of the subject's depth silhouette. The 3D points in the foot segment were then projected to a lateral plane to produce a side view of the foot segment. These projected points were normalized and centered for each frame as shown in the Figure 2(c). Fuzzy C-Means (FCM) clustering was performed on each frame of the depth image time series, considering two clusters (left and right foot) [10]. The distances between the cluster centers were recorded for each frame. Data points with fuzzy membership values ≥ 0.98 were considered for the analysis. This helped to remove noise around the foot area. The depth image frame with highest cluster center distance was considered as the ANT reach frame for a mSEBT trial. The two clusters in the ANT reach frame were assumed to be elliptical in shape. Two ellipses were fitted around the two clusters. The distance between the toe side vertex points on each eclipse were assumed as the anterior reach distance as shown in Figure 2(d). Finally, the percentage ANT reach distances were calculated from the absolute ANT reach distances.

As part of this investigation, different techniques were developed and tested to obtain ANT reach measurements from the depth images. Some of those techniques include, using only cluster distances or using only ellipse fits on the feet projections. However, a combination of both techniques worked best. FCM clustering and fuzzy memberships helped to clean the data and ellipses could fit on the cleaned data to find the toe area.

Statistical Analysis

The ANT reach distances (both absolute and normalized), were used for reliability tests. ICC (2,1)s were measured to evaluate interrater reliability, examining results obtained from the depth image analysis to the "gold standard" Vicon [4]. ICCs were evaluated using four different categories including, excellent ≥ 0.90, good = 0.70 – 0.89, fair = 0.40 – 0.69, and poor ≤ 0.39 [11]. To determine absolute reliability, standard error of measurement (SEM) [12] and smallest detectable difference (SDD) [13] were calculated. SPSS 24.0 (IBM, Armonk, NY) software package was used to analyze the data with significance level (α) set to 0.05 [4]. ICC, SEM and SDD were compared to previously reported normalized and absolute ANT reach distances, to manual inter-rater reliability measurements by Hyong et al. and Gribble et al respectively. [4, 7].

	Part A – Our Results (% ANT Reach)				
		ICC (2,1)	**95% CI**	**SEM**	**SDD**
L	Kinect-V	0.81	0.64-0.90	3.65	10.11
R	Kinect-V	0.84	0.67-0.92	3.98	11.04

	Part B – Results from Hyong et al. (% ANT Reach)				
		ICC (2,1)	**95% CI**	**SEM**	**SDD**
A	Manual	0.83	0.75-0.89	3.68	10.2

Table 1. Results on Normalized Anterior Reach Measurements. Part A: Interrater reliability for Vicon-Kinect from our study. Part B: Interrater reliability measure for manual observations by Hyong et al. [4]

		ICC (2,1)	95% CI	SEM (cm)	SDD (cm)
Part A – Our Results (Absolute ANT Reach)					
L	Kinect-V	0.75	0.54-0.87	3.19	8.85
R	Kinect-V	0.81	0.63-0.90	3.75	10.41
Part B – Results from Gribble et al. (Absolute ANT Reach)					
		ICC (1,1)	**95% CI**	**SEM (cm)**	**SDD (cm)**
A	Manual	0.88	0.80-0.94	-	-

Table 2. Results on Absolute Anterior Reach Measurements. Part A: Interrater reliability for Vicon-Kinect. Part B: Interrater reliability measure for manual observations by Gribble et al. [7]

RESULTS

The Kinect demonstrated good ICC reliability of absolute and normalized ANT reach distance measurements, for the right and left limb as compared to a "gold standard" Vicon system (Table 1A and 2A). Additionally, the Kinect demonstrated similar normalized ANT reach SEM and SDD values to previously reported manual measurement inter-rater reliability error rates by Hyong et al (Table 1B). Gribble et al. did not report SEM and SDD measurements in their study, only ICC values (Table 2B). It is important to note that in the studies conducted by Hyong et al and Gribble et al., ANT reach measurements were not subdivided into the left and right foot [4, 7]. Nevertheless, we believe that this comparison gives strength to the potential utility of the Kinect V2 depth camera within the clinical setting by comparing it to currently accepted error rates.

CONCLUSION

Automated customized software, using depth cameras such as a Kinect V2, offer promise to enhance clinical efficiency by reducing the need of tedious manual measurements while maintaining currently accepted practitioner error. In summary, we have developed a novel depth image analysis method to obtain ANT reach distances of the mSEBT. This method could be used for efficient widespread screening for injury prevention and risk assessments. Additionally, using this automated technique, clinicians may visually assess a client's potential deficit in neuromuscular control of the stance limb within the frontal and transverse plane with greater ease. In future investigations, we plan to obtain posteromedial and posterolateral measurements using similar techniques, as well as including a larger sample size.

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