8-2018

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IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 30, 2018, accepted August 3, 2018, date of publication August 10, 2018, date of current version September 5, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2864677

Low-Cost Experimental System for Center of Mass and Center of Pressure Measurement (June 2018)

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ABSTRACT Falls happen when the center of mass of body is outside of its base of support and the recovery of the center of mass back to the base of support failed. Balance ability is an essential ability needed for humans' daily routine activities. Improving balance ability should result in a better and more convenient way of living. There are various factors influence on balance ability. The focus of this paper is to investigate which factors have the greatest effect on balance. Balance ability is measured by deviations of center of pressure in both x-direction (side-to-side) and y-direction (front-to-back) with the age, height, body mass index, and location of body center of mass. Coordinates of subject's joints were tracked and recorded by a motion capture system with three cameras and then were used to calculate the coordinates of segment's mass center. The coordinates of whole body mass center were determined using the weighted segmental method. The trajectories of the center of pressure were tracked and recorded by a Wii balance board under five standing postures and slow sway movement along x-direction (side-to-side) situations. The information obtained from the center of mass and the center of pressure data analysis may assist with fall prediction and prevention. With a basic training on system operation, laypersons may use this affordable low cost system at home as an exercise tool to improve balance capability and reduce fall risk factors.

INDEX TERMS Balance, center of mass, center of pressure, motion capture system.

I. INTRODUCTION

Falls are the leading cause of fatal and non-fatal injuries for the elderly in US [1]. Nearly, 30% of elderly experience a fall [2]. The fear of falling is a prominent emotion among 36.2 percent of the elderly population and negatively affect their physical activity [3]–[5]. In US, medical costs on falls treatment have increased nearly one Billion dollars between the years of 2012 and 2015 [6]–[9]. This increase represents a significant burden for the US healthcare system, especially as the baby boomer generation gets older. The death of the elderly due to falls has increased significantly [10]. According to the Centers for Disease Control and Prevention report, the rate at which older Americans are dying from fall-related injuries has risen dramatically by 31% [1], [2].

Falls will happen if the center of mass (COM) is not within the base of support (BOS) [11], [12]. There are varieties of reasons make a person not be able to bring COM back to BOS. The reasons include lack of strength and balance ability due to aging. Therefore, the elderly population is at a higher risk of falls [13]–[22]. Prevent falls is a significant concern among the elderly population and their loved ones. Fall prevention programs emphasize balance, muscular strength and behavior modifications. They have been found to have positive outcomes and to be effective in reducing the incidence of falls [23]–[29].

To remain balanced, a person standing must be able to keep the vertical projection of their COM within their BOS [11], [12], [30]–[32]. Changes in location of the COM due to breathing could result in a progressively decaying balancing of the center of mass, which would result in a fall if no corrections were made. The balance control of disturbed standing is important for preventing falls of humans [30]–[34].

In this manuscript, a cheap and effective means by which to estimate the COM and the center of pressure (COP) was developed and tested. These measurements primarily will allow for an examination of the COM within all three planes. Camera recorded data were used to determine the segmental COM and whole body COM location in the X and the Z axis, while vertical ground reaction forces measured from a Wii Balance Board was used to determine the COP location which represent COM projection on the X and Y axis. The results demonstrate that this arrangement of instrumentation provide an adequate assessment of the stability of center of mass and postural sway, without using expensive force plate.

The remainder of this manuscript is organized as follows: Section 2 presents background and related works, experiment setup description is detailed in Section 3. Data acquisition and processing are explained in Section 4. Results are presented and discussed in Section 5, and followed by conclusion and future work in Section 6.

II. BACKGROUND AND RELATED WORKS

The COM is an important parameter that assists people in understanding human locomotion, and more importantly human balance. The human body's COM changes with posture changes [11], [30]–[33]. Typically, a human's COM is detected with a reaction board (force plate), the reaction board is a static analysis that involves the person lying down on the reaction board, and using the static equilibrium equation to find COM. The COM is an essential variable in human locomotion and balance studies. When related to falls, COM and its relation to postural sway are essential variables in fall prevention and prevention.

The distribution of mass is balanced around the COM and the average of the weighted position coordinates of the distributed mass defines its coordinates. The control of the COM with respect to the base of support is dependent on the point of application of the ground reaction forces known as the COP. The displacement of the COP is considered as a measure of body neuromuscular demand to maintain standing stability. The center of gravity (COG) is a point, which locates the gravity or weight of the body. Winter [33] gave the basic definitions on the COM and COG, and defined COG as the vertical projection of the COM onto the ground.

Determining the whole body COG position requires knowledge of the position and mass of the body segments. Estimation of the COM is based on information of body segments. The body is divided into discrete segments; these segments exist between joints [11], [34]. For instance, the forearm is a segment, represented by the area of the arm between the elbow and the wrist. In previous studies, the COM for each segment of the human body have been determined [11], [12], [33], [34], [45], [46]. Location of each segmental COM is described as the percentage of the length of segment. Total body COM position is calculated through an average of the weighted position coordinates.

A. OVERVIEW OF BODY SEGMENT MODELS

The most applied model for whole body center of mass estimation is the weighted segmental model. Using this model, the location of the whole body center of mass can be calculated without prior knowledge of the locations of COM for each segment. Various methods have been developed for the estimation of the center of mass and the center of pressure [35]–[46]. Benda *et al.* [44] used an eleven-segment whole body model for the COG calculation. Fig.1 (a) shows the whole body with 11-segment. Drillis *et al.* [45] reviewed methods for the determination of body segment parameters and surveyed body segments parameters, measurement techniques, and discussed body mass distribution models from Harless research. They used a fifteen-segment whole body model in their work. Fig.1 (b) shows the whole body with 15-segment.

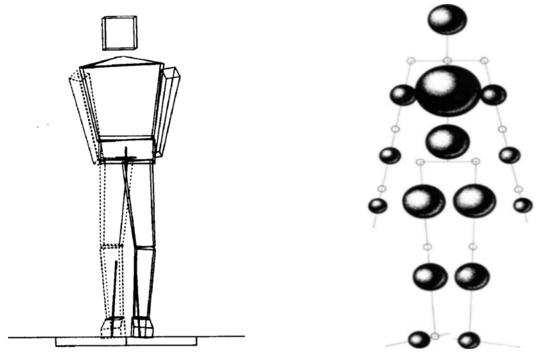

FIGURE 1. Human Body Models. (a) Body model with 11-segment (b) Body model with 15-segment.

When study quiet standing balance ability, inverted pendulum models are widely used [30]–[34]. Compare above two human body segment models, the 15-segment body model is more accurate to describe human body with movement. Instead of directly using 15-segment body model, we record positions of 18 joint locations and then determine the length of each segment from coordinates values.

B. OVERVIEW OF BODY SEGMENT PARAMETERS

The COM position can be identify the weight of each part of the body by using the anthropometric data that represent the segment weight expressed in percentages of total body weight as shown in table. Segments of human body are represented by the areas, which located between joint centers. Human body segmental anthropometric data are used to determine the location of each segment's center of mass. Each segment parameter is expressed as a percentage value. Typically, body segment parameters for standard size and shapes refer to adults.

The location of the segmental COM is described as a percent of segment length from the proximal joint. Anthropometric data generated by Winter [11], Jaffrey *et al.* [40], and Drillis *et al.* [45] are widely used in research. Body-segment length represent as a percent of height. The adapted results from [45] is summarized in Table 1.

The segment mass is described as a percent of total body mass. Table 2 shows results for average adults.

Based on the segment parameters, such as the length percentage of body height and mass percentage of whole body mass, the location of each segmental COM can be estimated. Because the whole body COM is a point equivalent of the body mass in the global reference system and is the weighted average of the COM of each segment in 3D space [33],

TABLE 1. Position of segmental center of mass of average adults [45].

Segment	Male	Female
Head and neck	50.02	48.41
Trunk	43.10	37.82
Upper arm	57.72	57.54
Forearm	45.74	45.59
Hand	79.00	74.74
Thigh	40.95	36.12
Shank	43.95	43.52
Foot	44.15	40.14

TABLE 2. Body segment mass parameters of average adults [45].

Segment	Male	Female
Head and neck	6.94	12.00
Trunk	43.46	23.85
Upper arm	2.71	18.07
Forearm	1.62	15.65
Hand	0.61	11.17
Thigh	14.16	25.20
Shank	4.33	22.70
Foot	1.37	5.80

the sum of the moments of each body segment should be equal to the moment of the whole body mass as shown in the following relationship:

$$\Sigma\,(m_i x_i) = MX \quad (1)$$

$$\Sigma\,(m_i y_i) = MY \quad (2)$$

$$\Sigma\,(m_i z_i) = MZ \quad (3)$$

where m_i represents the mass of the segment i, x_i, y_i, and z_i represent coordinates of the center of mass of segment i, M, X, Y, and Z represent body mass and coordinates of the body center of mass. However, the location of joints are not easy to determine, especially when a segment changes its position with respect to its adjacent joint, therefore it is very important to specify the boundary or range of joint in measuring the body segments.

However, all available segmental parameters from literature are suitable only for average shaped adults. Segmental parameter database is required for different groups of people considering influence of age, height, and body mass index (BMI) on the mass distribution on each body segment.

In our work, the length of each segment is not determined based on the percentage value of body height as suggested by literature [11], [12], [45]. We apply a motion capture system with three cameras to record subject movement. The 3D coordinates were generated through 18 markers, which were attached at joints positions. From joints' coordinates, we calculate the length of each segment. This method removed the effects of averaged parameter on each individual person's real segment length.

III. EXPERIMENT SETUP

A. COM TRACKING USING MOTION CAPTURE SYSTEM

The motion capture system included three OptiTrack Flex 13 cameras (shown in Fig. 2a) powered by an OptiTrack

(a) (b)

FIGURE 2. Motion capture system. (a) Motion Flex 13 camera. (b) OptiHub.

OptiHub 2 (shown in Fig. 2b) through a USB 2.0. The hub was connected to a UL certified AC adapter which converts the A/C input voltage from 100-240V to an output of 12V D/C. This allowed the hub to be plugged into any National Electrical Manufacturers Association (NEMA) 5-5 Type B 120V AC socket. Each hub output had a maximum voltage of 5V at 1A which is equal to the maximum input of the camera.

Prior to testing and recording, cameras were calibrated to insure data accuracy. Re-calibration was also performed for any changes of subject position and posture, and the distance to the cameras. To the best of knowledge, there is no standards or codes to follow for performing motion capture procedures. In this work, we developed our own standards for data recording, which included default location with optimal lighting and ambient temperature. Following this procedure, we were able to achieve more precise and accurate data capture for multiple recordings.

1) CAMERA ARRANGEMENT

The most critical issue was where to mount the three cameras. Since the view range of motion capture along the horizontal field is limited to a 56-degree angle, the subject standing outside of this capture range would prevent adequate motion capture. To provide an optimal capture volume, the view range from each camera should have overlap. Overlapping the views of the cameras insured that at least two cameras could capture each marker at all times, allowing for an adequate triangulation of its position in 2-Dimensional space. Because a height difference can provide a more comprehensive vertical field of view for the cameras to collect data, three cameras were mounted on a single stand at different heights.

A passive marker system was used to reflect infrared light back to each individual camera, allowing for triangulation. When the height of the testing subject and the type of movement changed, the location of the three cameras would need to be adjusted accordingly. All three cameras were mounted on one stand. The first camera was mounted parallel with the ground level at a height of 4 feet, the second camera was mounted at 6 feet 4 inches with an angle of 5 degrees facing downward, and the third camera was mounted at a height of 6 feet 6 inchs with an angle of 3 degrees facing down. With this arrangement, a recording area of 60 square feet was achieved for the test subject who is 5 feet and 9 inches high.

2) RECORDING PLANE SELECTION
To provide enough views for optical reflective markers and better estimate the center of mass in a 2-dimensional plane, the frontal plane was selected as the recorded plane.

3) MARKER PLACEMENT
It was found that most researchers placed markers in similar positions regardless of the software being used. In this study, to attain the most accurate results, optical reflective markers were attached to the clothes of tested subjects at major joints as closely as possible. To estimate the center of mass in 2-dimensions using segmental model shown in Fig.1, 18 markers were used. With the customizability of our recording system, each project can vary, and the marker placements is dependent on the test subject and the movements being recorded. Fig. 3 shows the optical marker placements in this study.

FIGURE 3. **Marker placement on tested subject.**

B. COP TRACKING USING WII BALANCE BOARD
To keep potential costs for the system at a minimum, based on review of the pertinent literature, studies have capered the accuracy of a Wii balance board to clinical grade force plates, and determined them to be comparable [46]. The BrainBlox program software was developed by Dr. Alaa Ahmed research group in the Department of Integrative Physiology at the University of Colorado Boulder was used to track and record data measured by Wii balance board. Fig. 4. Shows the Wii Balance Board used in this research.

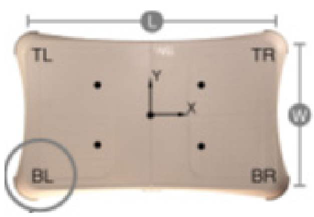

FIGURE 4. **Wii Balance Board with the coordinates [47].**

TL, TR, BL and BR represent top left, top right, bottom left and bottom right sensors, respectively. The origin of the coordinate system indicates the center of COP.

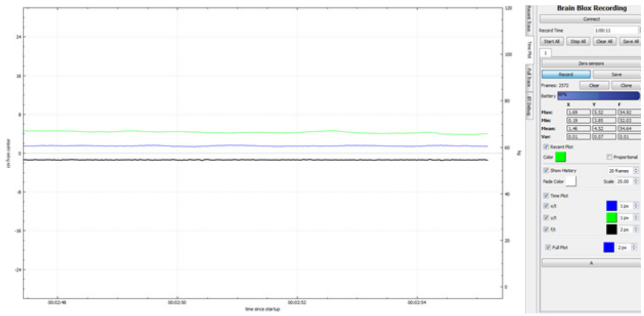

FIGURE 5. **BrainBlox software COP deviation graph.**

C. WII BALANCE BOARD CALIBRATION
To determine the accuracy of the output data obtained through the Wii Balance Board and to measure the accuracy of the data output from the computer software "BrainBlox", we placed a 45-pound dumbbell on each of the four sensors on the board assuming weight of 180 pounds for average normal adults. The different locations and configurations of dumbbells provided different centers of pressure in order to test the entire spectrum of the board sensors. In this work, each test was repeated six times, a precision uncertainty analysis was calculated. The Wii balance board was rated for a maximum weight of 330 pounds. We assumed there is no jumping or excessive force when operated [46].

D. WII BALANCE BOARD COMMUNICATION AND SOFTWARE
A Bluetooth was used to communicate Wii Balance Board with a computer. The COP position, vertical gravity force reaction, and vertical gravity force distribution on four-force sensor were track and recorded by BrainBlox program.

To help subject visualize their balance performance, the following three options were selected:

a). The location of COP was shown as a green circle; the origin of the coordinate system was shown as a square. The movement of the green circle represents how far the COP moves away from the center of COP, provides visualized information on subject's ability to maintain balance, and helps subjects adjust their standing posture to move COP back to the center of COP.

b). The deviation of COP along x and y directions away from the origin and the weight change with time were displaced in time history plot.

c). The trajectory of COP in x-y plane was shown under the full trace option.

IV. DATA ACQUISITION AND PROCESSING
In this work, the motions of the body COM using scaled body segment masses based on published anthropometric data and the motions of the reaction force COP using Wii Balance Board are reported. We adopted segment parameters suggested in [45] as shown in Tables 3, and 4.

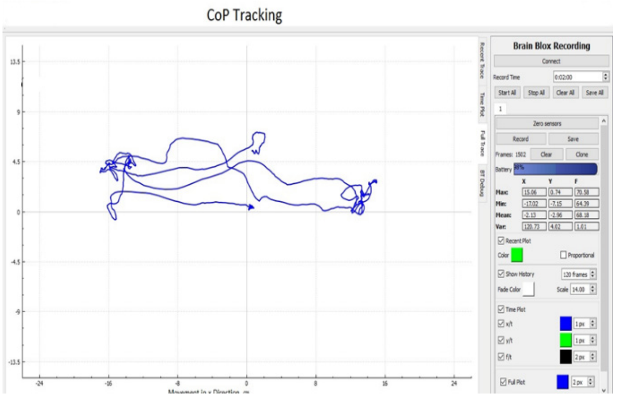

FIGURE 6. BrainBlox software COP trojectory graph.

TABLE 3. Relative weights of body segments in the percentage of body weight (adopted from [45]).

Segment	Subject 1	Subject 2
Head and neck	7.120	7.511
Upper trunk	36.04	35.643
Lower trunk	10.243	9.756
Upper arm	3.235	2.904
Forearm	1.813	1.594
Hand	0.833	0.679
Thigh	11.200	11.800
Shank	4.377	4.504
Foot	1.828	1.974

TABLE 4. Location of the mass centers measured from proximal joint from one subject [45].

Segment	Percentage of Segment Length
Head and neck	0.361
Upper trunk	0.497
Lower trunk	0.518
R. Upper arm	0.427
L. Upper arm	0.432
R. Forearm	0.417
L. Forearm	0.402
R. Hand	0.361
L. Hand	0.357
R. Thigh	0.430
L. Thigh	0.569
R. Shank	0.443
L. Shank	0.494
R. Foot	0.436

A. COM DATA ACQUISITION and PROCESSING

In order to find the center of gravity position of a subject, length and shape information mass of each segment are required to estimate the mass, and precisely determine the center of mass position of the subject body segments. The whole body model used in this study employed 15 body segments: the left and right feet, shanks, thighs, right upper arms, forearms, hands, and the pelvis, trunk, and head (Fig. 1 (b)).

In order to identify the location of the whole body center of mass, we generated an excel spreadsheet, which was able to calculate and illustrate the center of mass for each frame of a motion recording. The single frame excel sheet was used as a reference when running MATLAB Code. The developed MATLAB code calculated and displayed the center of mass for the tested subject through all frames within the same recording. There are several methods for finding COM of whole body. The Reaction Board Method measures the CG location based on the principle of static equilibrium (i.e., analysis of a static or stationary position of objects) in which the sum of all moments or torques acting on a system about a reference axis of rotation (A) equals zero. Segmentation Method uses the inertial properties of individual body segments, the location of each segment, and the methods of equilibrium analysis to determine the CG of the whole body. This method is much easier than the integration method for a rigid body since the integration is replaced with the algebraic sum of various component parts.

B. MOTION RECORDING AND DATA ANALYSIS

When the test subject swayed from left to right, coordinates of each marker captured by cameras were exported from the cameras to Excel spreadsheet that was supplied by the OptiTrack's Motive software. The X, Y positions of each marker are used in the single frame COM estimation spreadsheet. The Single Frame COM estimation calculates and plots the COM as well as calculates the segmental body lengths that are needed as inputs for the MATLAB COM estimation code. Single frame COM estimation and coordinates generated from work in [46] are shown in Table 5.

TABLE 5. Single frame mass center estimation from [40].

	PROXIMAL		DISTAL		LENGTH	SEGMENT CM		MASS	TORQUE	
	X	Y	X	Y	PERCENT	X	Y	PERCENT	X	Y
R FOOT	0.33783	0.04338	0.2759	0.04095	50.00%	0.30686	0.042163	1.33%	0.00408	0.00056
L FOOT	0.02905	0.04467	0.09568	0.0399	50.00%	0.06237	0.042283	1.33%	0.00083	0.00056
R SHANK	0.27795	0.47672	0.33783	0.04338	41.90%	0.30304	0.295153283	5.35%	0.01621	0.01579
L SHANK	0.0742	0.46958	0.02905	0.04467	41.90%	0.05528	0.291539129	5.35%	0.00296	0.0156
R THIGH	0.32504	0.98397	0.27795	0.47672	42.80%	0.30489	0.766869856	11.75%	0.03582	0.09011
L THIGH	0.03599	0.97566	0.0742	0.46958	42.80%	0.05235	0.759053188	11.75%	0.00615	0.08919
R UP ARM	0.3436	1.48613	0.61762	1.41368	45.80%	0.4691	1.452948648	2.90%	0.0136	0.04214
L UP ARM	-0.0066	1.48463	-0.2697	1.38126	45.80%	-0.1271	1.437287708	2.90%	-0.0037	0.04168
R FOREARM	0.61762	1.41368	0.84687	1.44274	43.40%	0.71711	1.42629387	1.57%	0.01126	0.02239
L FOREARM	-0.2697	1.38126	-0.5126	1.3565	43.40%	-0.3751	1.370514462	1.57%	-0.0059	0.02152
R HAND	0.84687	1.44274	1.01097	1.41806	46.80%	0.92367	1.431187356	0.50%	0.00462	0.00716
L HAND	-0.5126	1.3565	-0.6621	1.34003	46.80%	-0.5826	1.348794508	0.50%	-0.0029	0.00674
HEAD	0.15357	1.7805	0.16816	1.44303	55.00%	0.16159	1.5948919	8.20%	0.01325	0.13078
						0	0		0	0
R TRUNK	0.32504	0.98397	0.3436	1.48613		0.32504	0.983972		0	0
L TRUNK	0.03599	0.97566	-0.0066	1.41368		0.03599	0.975655		0	0
MIDTRUNK	0.1805	0.9798	0.1685	1.4499	50.00%	0.17451	1.21485975	45.00%	0.07853	0.54669
								100%	0.1748	1.0309

Single frame COM estimation and coordinates generated from work in [45] are shown in Table 6.

From Tables 5 and 6, we can apparently conclude that the location of the whole body center of mass will change with segment parameters change. The length percentage of body segment can be measured for each individual. However, the mass percentage of body segment can only be estimated based on the volume and density of each segment. The each segment mass values showed in literature were obtained from measurement of cadavers. In our future work, a mathematical model will be developed to calculate the volume of each body segment based on the shape and length of the segment.

TABLE 6. Single frame mass center estimation using segment parameters in [45].

	PROXIMAL		DISTAL		LENGTH	SEGMENT CM		MASS	TORQUE	
	X	Y	X	Y	PERCENT	X	Y	PERCENT	X	Y
R FOOT	0.33783	0.04338	0.2759	0.04095	43.60%	0.31083	0.042318904	1.83%	0.00569	0.00077
L FOOT	0.02905	0.04467	0.09568	0.0399	43.60%	0.0581	0.042588152	1.83%	0.00106	0.00078
R SHANK	0.27795	0.47672	0.33783	0.04338	44.30%	0.30448	0.284753051	4.38%	0.01334	0.01247
L SHANK	0.0742	0.46958	0.02905	0.04467	49.40%	0.0519	0.259670954	4.38%	0.00227	0.01137
R THIGH	0.32504	0.98397	0.27795	0.47672	43.00%	0.30479	0.76585536	11.20%	0.03414	0.08578
L THIGH	0.03599	0.97566	0.0742	0.46958	56.90%	0.05773	0.687696049	11.20%	0.00647	0.07702
R UP ARM	0.3436	1.48613	0.61762	1.41368	42.70%	0.4606	1.455194412	3.24%	0.0149	0.04708
L UP ARM	-0.0066	1.48463	-0.2697	1.38126	40.20%	-0.1124	1.443076652	3.24%	-0.0036	0.04676
R FOREARM	0.61762	1.41368	0.84687	1.44274	41.70%	0.71321	1.425799935	1.81%	0.01291	0.02581
L FOREARM	-0.2697	1.38126	-0.5126	1.3565	40.20%	-0.3674	1.371306686	1.81%	-0.0066	0.02482
R HAND	0.84687	1.44274	1.01097	1.41806	36.10%	0.90611	1.433828437	0.83%	0.00752	0.0119
L HAND	-0.5126	1.3565	-0.6621	1.34003	35.70%	-0.566	1.350622567	0.83%	-0.0047	0.01121
HEAD	0.15357	1.7805	0.16816	1.44303	36.10%	0.15884	1.658672218	7.12%	0.01131	0.1181
						0	0		0	0
R TRUNK	0.32504	0.98397	0.3436	1.48613		0.32504	0.983972		0	0
L TRUNK	0.03599	0.97566	-0.0066	1.41368		0.03599	0.975655		0	0
MIDTRUNK	0.1805	0.9798	0.1685	1.4499	50.00%	0.17451	1.21485975	45.00%	0.07853	0.54669
								100%	0.1731	1.0206

C. COP DATA ACQUISITION

The following five standing and sway situations are recorded:

1) Stand on Wii Balance Board with their feet 30 cm apart and eyes open, find the balance position first, and then maintain balance for 40 seconds.
2) Stand on Wii Balance Board with their feet 30 cm apart, find the balance position, and then with eyes closed, maintain balance for 40 seconds.
3) Stand on Wii Balance Board with their feet together and eyes open, find the balance position first, and then maintain balance for 40 seconds.
4) Stand on Wii Balance Board with their feet together, find the balance position, and then with eyes closed, maintain balance for 40 seconds.
5) Stand on Wii Balance Board with their feet 30 cm apart and eyes open, find the balance position, and then sway from center to left and back to center, then sway from center to right and back to center for 40 seconds.

D. COP DATA PROCESSING

For the subject, five instructed performances were recorded by Brain Blox Software and saved as five named data files with no extension format. To read and analyze the recorded data with another program, the named data files with no extension format must have an extension. In this work, the recorded data form Wii Balance Board were read manually into Excel file with eight columns. The corresponding information was descripted as following:

- Column A: Time in milliseconds elapsed since program was opened
- Column B: Time in seconds since program was opened by setting the starting time as zero
- Column C: Force from sensor 1 (top left) in kilograms
- Column D: Force from sensor 2 (top right) in kilograms
- Column E: Force from sensor 3 (bottom left) in kilograms
- Column F: Force from sensor 4 (bottom left) in kilograms
- Column G: COP distance from center in the x-direction in centimeters
- Column H: COP distance from center in the y-direction in centimeters
- Column I: Total force (sum of columns 2-5) in kilograms

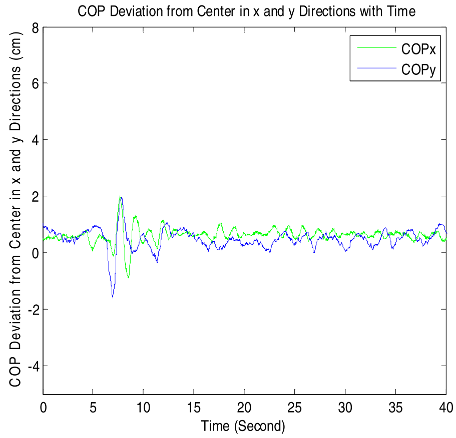

FIGURE 7. COP deviation feet apart eyes open.

The location of COP was calculated using a weighted average of the location and the measured force value of the four force sensors of the WBB as shown in follows:

$$COP_x = \frac{L}{2}\frac{(TR+BR)-(TL+BL)}{TR+BR+TL+BL} \tag{4}$$

$$COP_y = \frac{W}{2}\frac{(TR+TL)-(BR+BL)}{TR+BR+TL+BL} \tag{5}$$

Where BL, BR, TL and TR are the calibrated force values from the bottom left, bottom right, top left and top right sensors respectively. L and W represent length and width of Wii Balance Board. The body sway was measured by COP_x in the side-to-side direction, and COP_y in the front-to-back direction. COP_x and COP_y are listed in Column G and H, respectively.

E. DATA ANALYSIS USING MATLAB PROGRAM

A MATLAB code was developed for data analysis. Results from MATLAB program under five situations were shown in the following figures:

1. Stand with their feet 30 cm apart and eyes open, maintain balance for 40 seconds.

The figure shows that the sway in y-direction more than x-direction when standing feet apart. With eyes open, balance was recovered faster in both x and y directions.

2. Stand with their feet 30 cm apart and eyes closed, maintain balance for 40 seconds.

The figure shows that the sway in y-direction more than x-direction when standing feet apart. With eyes closed, balance was not recovered within 40 seconds.

3. Stand with their feet together and eyes open, maintain balance for 40 seconds.

The figure shows that the sway in y-direction more than x-direction when standing feet together. With eyes open, balance was recovered between 12-25 seconds in both x and y directions.

4. Stand with their feet together and eyes closed, maintain balance for 40 seconds.

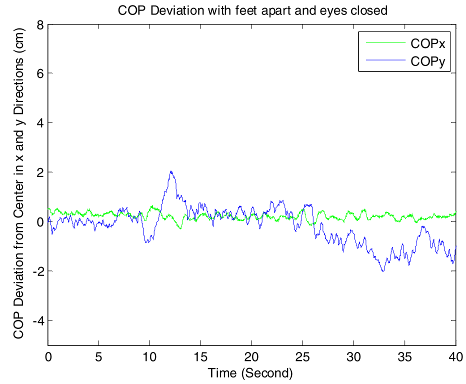

FIGURE 8. COP deviation feet apart eyes closed.

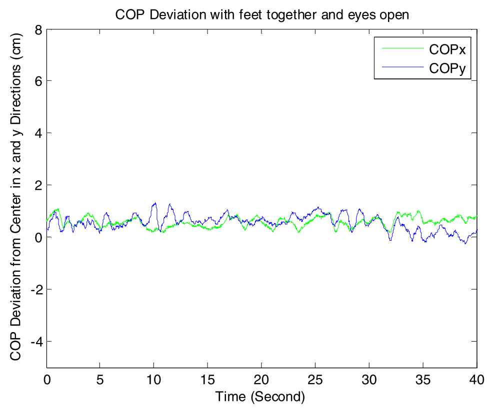

FIGURE 9. COP deviation feet together eyes open.

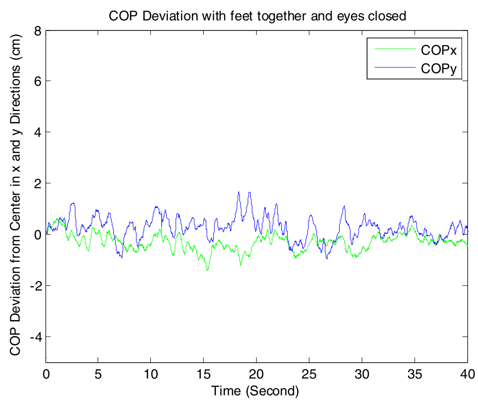

FIGURE 10. COP deviation feet together eyes open.

The figure shows that the sway in both x- and y-direction, sway more in y-direction than x-direction when standing feet together and eyes closed. Balance was not recovered between 12-25 seconds in both x and y directions.

5. Stand with their feet 30 cm apart and eyes open, sway from center to left and back to center, then sway from center to right and back to center for 40 seconds.

When sway side-to-side, the COP was supposed only changes sway direction, however, COP deviation along y-direction was observed. From the figure, we noticed that

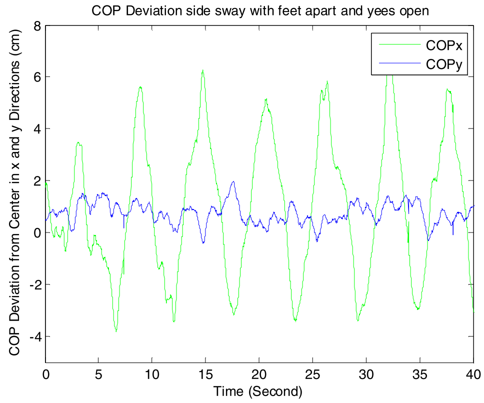

FIGURE 11. COP deviation feet apart eyes open sway side-to-side.

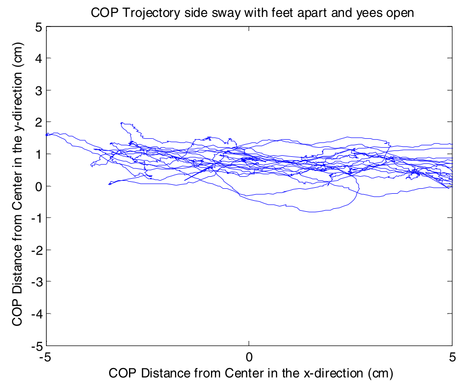

FIGURE 12. COP phase plane feet apart eyes open sway side-to-side.

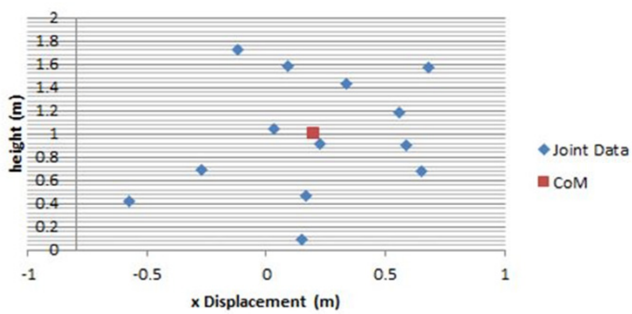

FIGURE 13. COM tracking graph when leaning to left.

the left and right sway limits are not the same. The large sway limit is coincident with the dominate feet.

V. RESULT AND DICUSSION

A. COM ANALYSIS RESULTS USING EXCEL SPREAD SHEET

A red diamond presents the tracked COM location, while all markers are shown as blue squares. The tracked movement is plotted in Fig. 13 when the test subject is leaning left.

Since the exported Excel sheet supplied by the motion capture software displays the Cartesian coordinates of each frame, and only tracks the COM in a single frame, estimating the COM from every single frame would be time- consuming.

Therefore, there is a need for a more efficient method for the COM estimation. In this work, a MATLAB code was developed to model the single frame estimation, calculate, and plot the COM for every frame in the recording. The graph shown in Fig. 13 was produced by this single frame excel sheet from Table 2. While the graph shown in Fig. 14 was the first frame in the MATLAB produced graphs.

B. COM ESTIMATION BY MATLAB CODE

Using the system, one can view the location of COM, COP, and study a subject balance capability. In Fig. 14, the body COM is located around the middle of the body between two hip markers and above the belly button. Determining whether the subject has good balance is relatively easy because the center of mass is within the subject's base of support. We calculated the base of support by measuring the area of the subject's foot. In Fig. 14 the base of support is between the ankle markers because the subject is balancing on both feet.

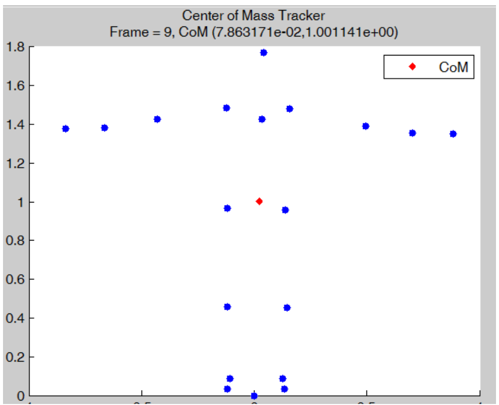

FIGURE 14. COM tracking when subject standing straight.

The MATLAB code was written to body mass center when subject moved from the left to the right. The code calls the Excel sheet data, which are exported from the motion capture system, which has 18 markers. The body center of mass is calculated using Eq. 1 and Eq. 2 where the Cartesian coordinates variables are provided automatically from the exported Excel file. The mass and length percentages of each segment is a constant and given from Table 1, and they are manually added to the MATLAB code. Moreover, each segment position, which is the difference between distal coordinate and proximal coordinate that is manually added to the MATLAB code after it has been calculated using the single frame Excel sheet shown in Table 2. The order of each of the mass, length, and position of segments is in the following order as discussed in our previous work [44]: right elbow, right hip, right wrist, left hip, head, left knee, right shoulder, right toe, left toe, left shoulder, left elbow, left wrist, clavicle, right heel, left heel, right knee, left fingers, right fingers. Then, the code sums up all the segments' mass of the whole body and create a plot that tracks the center of mass. The following plots are a sample of a quiet standing situation, to the left and leaning to the right. All three situations were captured and recorded from one single test subject. In the left-leaning situation, the data and plot show a poor balance practice by the subject where the center of mass is entirely out of the base of support. On the other hand, the right-leaning data shows a balanced subject.

In this recording, the subject lost his balance when leaning on his left foot. The exact moment where he lost his balance, was able to be determined. Fig. 15 shows a different situation. One can see the body mass center is located outside the subject's base of support. Therefore the subject lost his balance. In Fig. 15, the base of support is the area of a single foot.

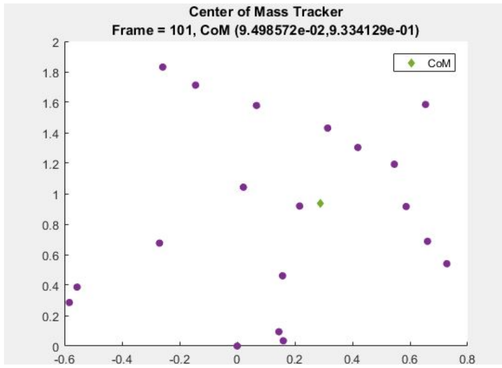

FIGURE 15. COM tracking graph when leaning to left.

To compare the body center of mass location between the leaned to the left and the starting position, we overlapped two tracking plots as shown in Fig. 16.

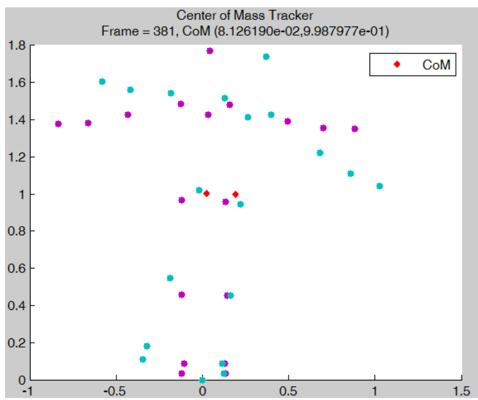

FIGURE 16. COM comparison when subject leans to left.

In Fig. 15 and 16, the center of mass is shown to be within the subject's single foot base of support. In this recording, the subject is leaning on his right foot, with good balance. From studying just these three figures, it becomes apparent that the subject maintains good balance if he leans to the right, as well as stands on both feet. Further observation, however, shows that the subject had a hard time maintaining balance while leaning to the left. This, experimental setup demonstrated how this product could be a beneficial assessment test for assisting people in find their balance weakness. For example, the testing subject may want to focus harder when balancing on his left foot.

TABLE 7. Defined adjusted COM locations

BMI	Adjust COM
<20	1.05 of Normal COM
20-25	1.00 of Normal COM
25-30	0.975 of Normal COM
30-35	0.95 of Normal COM
35-40	0.925 of Normal COM
40-45	0.90 of Normal COM
45-50	0.875 of Normal COM
>50	0.85 of Normal COM

Body sway was measured by the deviations of the center of pressure locations over time. From the observation, recording, and analysis, one may conclude that the subject can maintain balance if just a small range of sway happens. In Fig. 17, the subject begins to lean on his right foot. By observing the y-displacement, there is a small dip, then a large spike reaching just over positive one centimeter. This indicates that the subject lost balance, and a spike in postural sway was observed. As time continues, the subject went from left leaning to right, then back to the left and finally on both feet. His postural sway for both the single foot improved as time went on. There is little to no displacement sway in center of pressure when the subject is on both feet, indicating good balance as shown in Fig. 17.

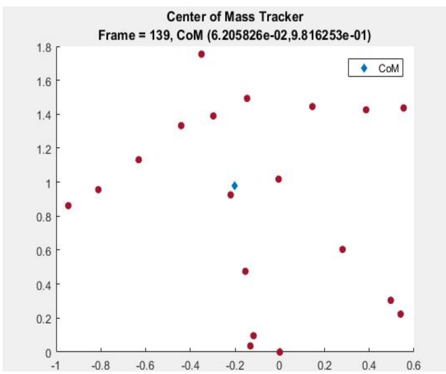

FIGURE 17. COM tracking when subject leans to right.

C. EFFECTS OF AGE, HEIGHT, AND BMI ON COM AND COP

In this section, we analyze the effects of age, height, and BMI on the whole body COM position, COP movement range on x- and y-directions under four testing situations.

1) COM LOCATION CHANGES WITH BMI

The COM location is depended on sex and BMI. Person with normal BMI, the COM location of a female is 0.532 of the height, while for male, the COM location is 0.560 of height. However, when BMI changes, the COM location will change accordingly. In this study, we define the new COM location, i.e., the adjusted COM based on the BMI range as shown in Table 7.

2) COP DEVIATION ALONG X- AND Y-DIRECTION

In Fig. 18, larger deviations of COP are observed when standing feet together than feet apart. Therefore, it is more difficult to maintain balance than with feet apart. With eyes closed, larger side-to-side sway motions were observed than with eyes open.

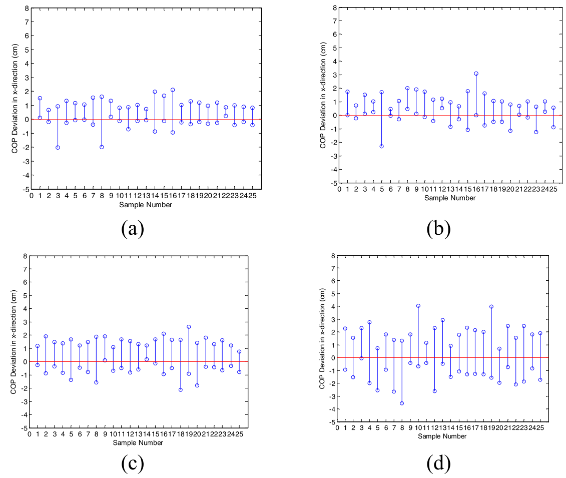

FIGURE 18. COP deviation on x-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.

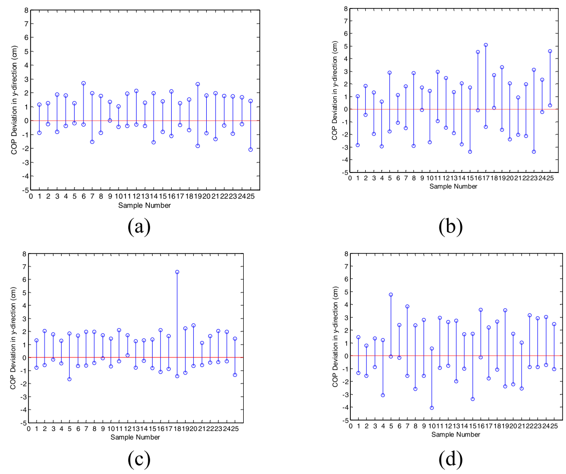

FIGURE 19. COP deviation on y-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.

From Fig. 19, standing with feet together, the results show that it is difficult to maintain balance than with feet apart; with eyes closed, larger front-to-back sway motions were observed than with eyes open. Significant larger deviation range shows on subject 18 during feet together with eyes open than any other three situations even with eyes closed in both feet apart and feet together. We noticed that during testing and recording process, the subject was disturbed and distracted by his peers around him. The subject did not fully concentrated during that test. The displacement of recorded data for the subject showed special reaction due to extreme disturbance. The test was not special test on environmental reaction.

Compare Figs. 18 and 19, in general, COP deviations in y-direction are noticeable larger than of x-direction under tested 4 situations.

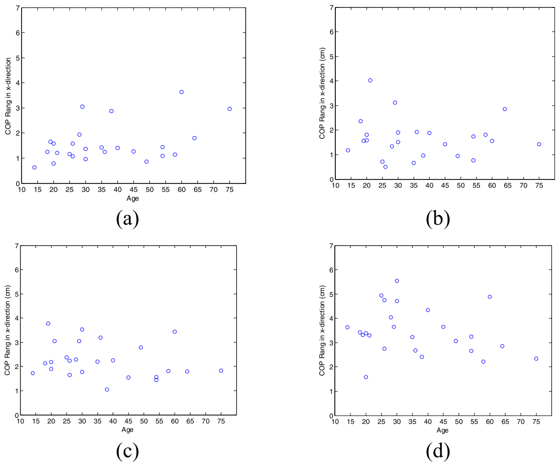

FIGURE 20. **COP deviation range change on x-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

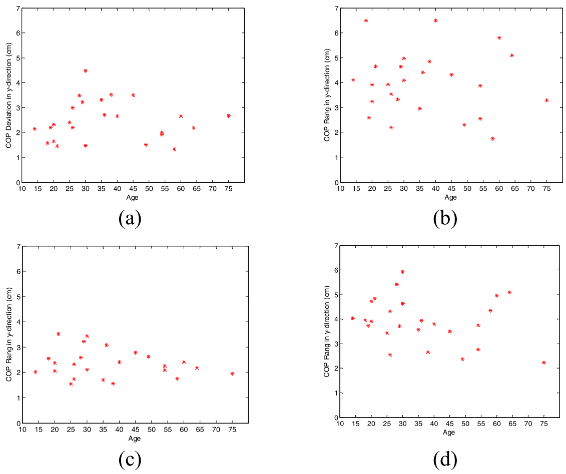

FIGURE 21. **COP deviation range change on y-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

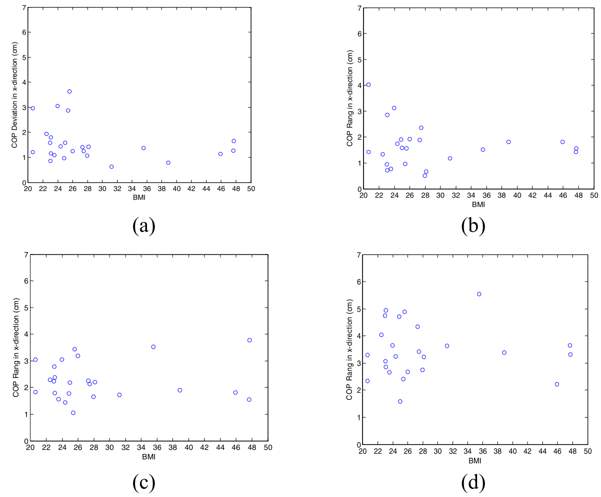

FIGURE 22. **COP deviation range change on x-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

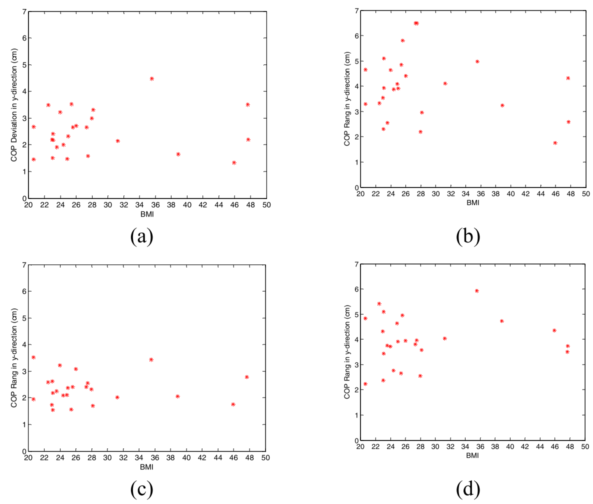

FIGURE 23. **COP deviation range change on y-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

3) COP DEVIATION RANGE CHANGES WITH AGE IN X-AND Y-DIRECTION

Fig. 20, shows standing with feet together is more difficult to maintain balance than with feet apart, the range of deviation changes with age, and with eyes closed, larger front-to-back sway motions were observed than with eyes open.

From Fig. 21, although there are no significant difference between standing with feet together and feet apart, the results show difficulty to maintain balance with eyes closed, larger front-to-back sway motions were observed than with eyes open.

4) COP DEVIATION RANGE CHANGES WITH BMI IN X-AND Y-DIRECTION

Fig. 22 shows no significant difference between eyes open and eyes close when stand with feet apart. However, standing with feet together, it shows difficulty to maintain balance with eyes closed; larger side-to-side sway motions were observed than with eyes open.

From Fig. 23, there are no significant difference between standing feet apart and feet together both with eyes open and eyes closed. However, larger COP front-to-back sway deviation are observed when eyes closed than with eyes open, both for standing with feet apart and feet together.

5) COP DEVIATION RANGE CHANGES WITH HEIGHT IN X-AND Y-DIRECTION

In Fig. 24, there are no significant difference between standing feet apart and feet together both with eyes open, and feet apart with eyes open and eyes closed. Noticed difference is observed when feet together and eyes closed for height range from 1.5 m to 1.80 m, only the 1.83 m high subject maintain

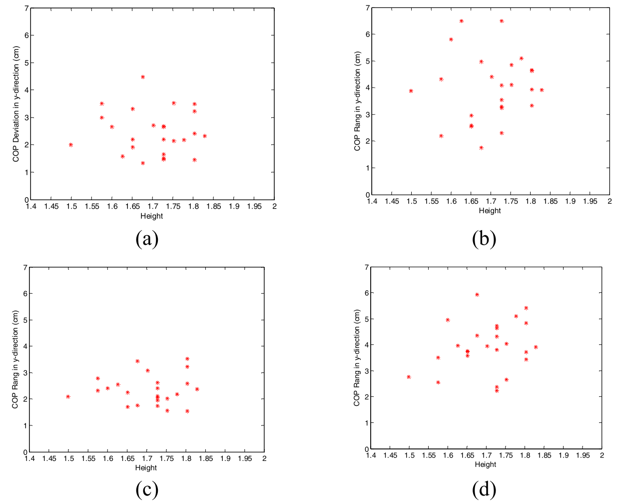

FIGURE 24. **COP deviation range change on x-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

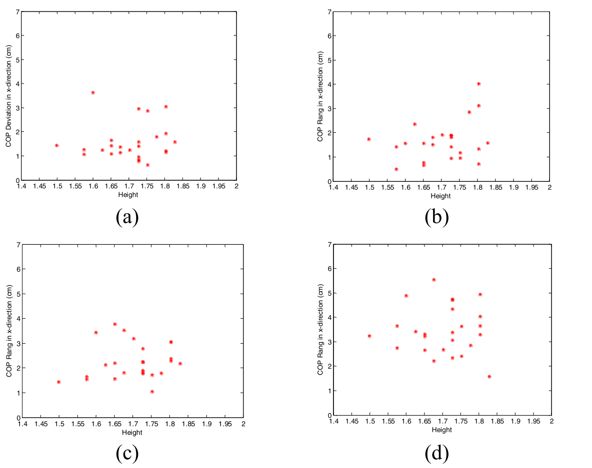

FIGURE 25. **COP deviation range change on y-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

balance very well. To relate balance with height, more sample data need to be recorded.

From Fig. 25, there are significant difference between eyes open and eyes closed for both standing feet apart and feet together. It was surprise to notice that with eyes open, standing feet together even balanced better than feet apart.

6) COP DEVIATION RANGE CHANGES WITH ADJUSTED COM POSITION IN X-AND Y-DIRECTION

From Fig. 26, we observed that standing feet apart, the sway range increases 0.5-1 cm when eyes closed than eyes open for subjects with lower COM. When standing feet together, the sway range increases 1.5-3 cm when eyes closed than eyes open for subjects with lower COM. There are significant difference between feet apart with eyes open and feet together with eyes closed.

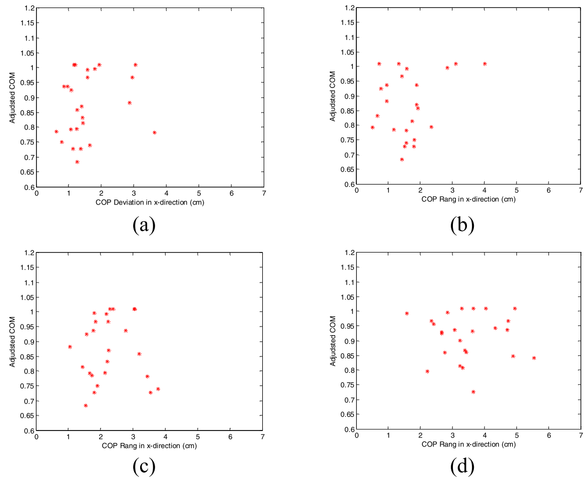

FIGURE 26. **COP deviation range change on x-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

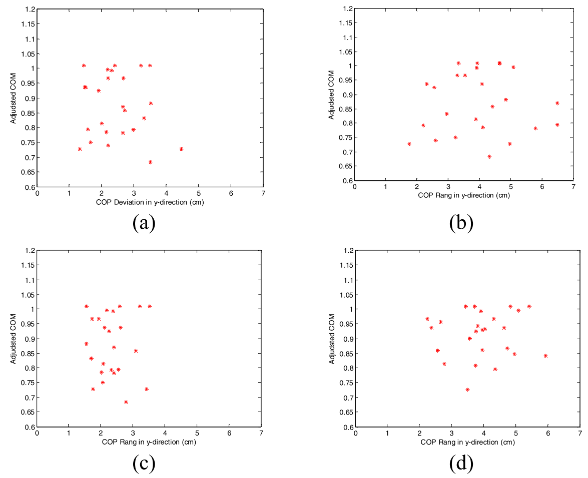

FIGURE 27. **COP deviation range change on y-direction. (a) feet apart with eyes open. (b) feet apart with eyes closed. (c) feet together with eyes open. (d) feet together with eyes closed.**

From Fig. 27, when standing feet apart, the sway range increases 0.5-3.5 cm when eyes closed than eyes open for subjects with lower COM. When standing feet together, the sway range increases 1.-3.5 cm when eyes closed than eyes open for the subject with lower COM. There are no significant difference between standing feet apart and feet apart, both with eyes open and eyes closed.

VI. CONCLUSIONS AND FUTURE WORK

In this work, a small, inexpensive, accurate and reliable 2D motion capture system to record and track the COM and COP of a human subject is developed. Whole body COM was tracked by a motion capture system with three cameras mounted on one camera stand. The standard parameters of length ratio and the mass ratio of each segment of the body for average shape and size male and female were used in our calculations. We compared the results acquired from the Wii

Balance Board and computer software program to the theoretical calculated data obtained using traditional measuring devices and techniques such as a tape measure for length and a digital scale for weight. Typically, COP is determined through force platform. Use of Wii Balance Board with a compatible output program reduced the cost of the system by 5,000-10,000 dollars. The results of the experiment revealed that the Wii Balance Board is approximately 98% accurate when measuring the magnitude of force placed on the board. The COP position calculated from Wii Balance Board is 90

- With eyes open, changing from standing with feet apart to feet together, all subjects were able to maintain balance, even though with feet together, more deviation of COP was observed than feet apart.
- With eyes closed, changing from standing with feet apart to feet together, all subjects have difficulty to maintain standing still, based on the trajectories of COP, more front-to-back movement than side-to-side movement were observed.
- With eyes open, feet apart and sway side-to-side, we noticed that the deviation of COP was varied with the speed of sway. When subject sway faster, the deviation of COP along y direction decreased.
- During standing with feet apart, with eyes open helped subjects maintain balance in terms of keeping COP as close as possible to the center of COP. With eyes closed, subjects lost the vison sensor feedback,

We believe this system could be a model system for minimally funded research institutions, small physical therapy practices or local high schools who are trying to study mass center and pressure center. One advantage of this system over traditional systems is portability. Designing a cart to organize and carry all of the testing equipment could make the system even more portable would be to design a cart to organize and carry all of the testing equipment. More cameras would increase the accuracy of the data gathered, and allow the system to use the more advanced 3D center of mass estimation models. This study demonstrates the ability to measure accurate and repeatable results with this equipment, but it would be much more versatile if more cameras were added in the future. For 3D tracking, a minimum of four cameras is recommended by OptiTrack. Thus in future designs this system may employ four or more cameras, allowing for the capture of 3D data for center of mass calculations, greatly increasing its utility within the commercial as well as clinical applications. Overall, this study demonstrates that technology, which has generally been reserved for very costly laboratory environments, can be accessible for both laypersons, as well as clinical settings with limited budgets.

ACKNOWLEDGMENT

The author would like to thank Dr. Alaa Ahmed of the University of Colorado Boulder for providing a computer program for Wii Balance Board.

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