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Body Sway Measurement for Fall Risk Assessment Using Inexpensive Webcams

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***Abstract*—In this paper, we present a method for extracting body sway parameters from a three-dimensional voxel reconstruction, which is built using silhouettes captured from two calibrated web camera views. The results were validated with a Vicon motion capture system. Experiments were conducted in which subjects stand and sway in the anterior-posterior direction and then in the lateral directions with two different frequencies. In addition, experiments were also conducted where subjects walked in a straight path at different speeds. Through the experiment, the Vicon cameras recorded the motion of reflective markers attached to subjects, and our two calibrated cameras captured the images. Good agreement was found with our system compared to the Vicon results, given the limitation of voxel space resolution and frame rate. The development of this technology provides potential capability of measuring body sway in daily living environment for elderly people, and can be used as part of a balance, stability and fall risk assessment tool.**

I. Introduction

Balance is generally defined as a person's ability to maintain or restore the equilibrium state of upright stance, without having to change the base of support [1], and it is a crucial aspect to avoid injury for elderly people. Balance is often assessed as the amount of postural sway (also called body sway) of the human body. Studies have suggested falls in the elderly are attributed to difficulties adapting one's balance in response to changes in sensory information [2], as well as increased sway in the anterior-posterior and medio-lateral directions compared to young adults [3]. Body sway is defined as the slight postural movements made by an individual in order to maintain a balanced position, and can be measured by the total displacement of the center of mass relative to the base of support over time. Body sway has been assessed for static balance and dynamic balance conditions, depending on whether the base is stationary or moving (such as standing or walking) [4].

Through the years, many different balance tests [5] and measurements [6,7] have been developed to provide appropriate information of balance capabilities during standing. The selection of a suitable method generally depends on the test subjects population and specific objectives. Normally, one single assessment technique could not be claimed and used as a true indicator of the overall integrity of the balance control system. For example, functional balance scales are easy to perform and suitable for daily clinical use, but not always accurate enough. Therefore, new technologies are necessary to give more detailed information about postural balance. Typically, the term "body sway" is used to describe the extent of the center point of pressure (COP) or the center of gravity (COG) (same as the center of mass COM) excursions. Body sway can be measured with a simple technology, such as using a "swaymeter" [8] or Wright's ataxiameter [9]. The swaymeter measures displacements of the body at the waist level, whereas the ataxiameter can be used to define sway as an angular movement of the body around the ankle joint.

One of the more accurate and most popular computerized laboratory systems for evaluating postural stability is the force platform. It is used to measure spontaneous body sway with the subject standing on it [10] or the subject's response to an applied postural perturbation [11]. The basic principle of the force platform test is to measure the movements of the COP that reflect both the horizontal location of the COG and the reaction forces due to muscular activity. Based on COP positions, typical parameters in platform measurements are the mean COP position which can be used as a reference point for base of support, anterior-posterior and lateral sway, the length of the sway path as well as sway velocity and sway area.

More recently, marker-based motion capture and analysis systems have been used for body sway measurement. By measuring the positions of the light-emitting markers, the position of the body segments can be tracked and, then the COM position can be calculated. One advantage of using a motion capture system is the capability of measuring body sway during normal walking [12] and for longer periods of time.

Although a motion capture system can provide accurate body sway information, the system is expensive and requires individuals to wear markers, and the test can only be performed in the lab or clinic environment. Markerless vision based motion capture provides a potential alternative for affordable capture of human motion in a wide range of settings, and has received a great deal of attention from the computer vision and biomechanics community. Such work includes using a markerless image processing algorithm to estimate the anterior/posterior trajectory of the center of mass from video sequences obtained from commercially available systems, while standing with stable and unstable support [13]. Also, researchers have demonstrated using a

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single, uncalibrated camera to measure clinically meaningful statistics of standing postural sway among an elderly balance-impaired cohort [14]. We have developed a two-camera system to measure body sway during both standing and walking using inexpensive web cameras. Our approach of using 3D voxel data has eliminated the limitation of a controlled walking path, and is thus suitable for daily assessment in the home environment.

Section II describes the body sway measurement methodology. Section III presents validation experiments, results and discussion. Section IV summarizes.

II. Body Sway Measurement Methodology

A. 3-D Voxel Reconstruction from Silhouettes

As an initial stage in the analysis, a silhouette extraction is performed to segment the human body from the background. This step not only defines the region of interest, but also helps protect the privacy when monitoring an elderly person in the normal daily living environment. Our research shows that elderly residents do not consider the use of silhouette imagery to be a privacy invasion [15]. Fused texture and color features are used for background subtraction [16].

Our three-dimensional human model, called voxel person, described and used in [17,18], is constructed in voxel (volume element) space by back projecting silhouettes from multiple camera views. A voxel is a three dimensional volume (a non-overlapping cube) resulting from the discretization of the environment. Here, the voxel resolution is 1x1x1 inch. An intrinsic model of each camera is estimated using the Camera Calibration Toolbox from [19].

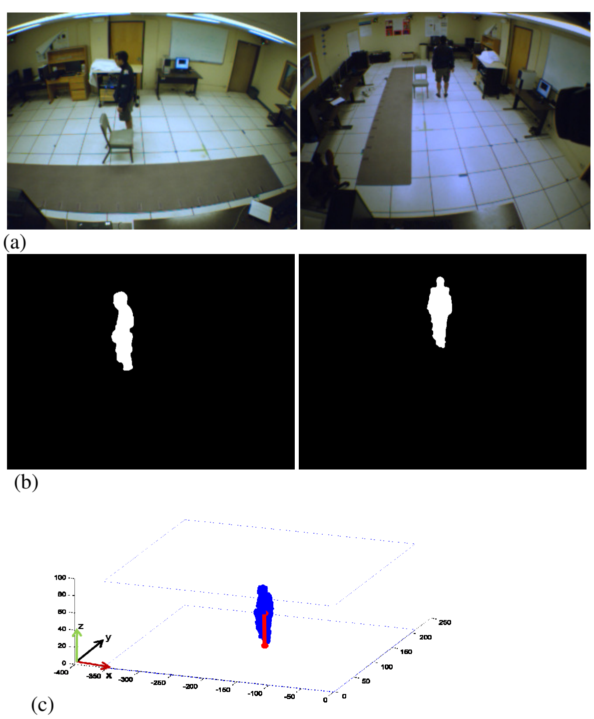

Fig.1 (a) Two raw camera images monitoring the same scene. (b) Human silhouettes (c) The reconstructed three-dimensional voxel person. The reference point and body centroid are denoted in red.

The 6 DOF location (position and orientation) of each camera in the environment is computed independently using correspondences between a set of measured 3D locations in the environment and pixels in the camera image. Given the optimized location, along with the intrinsic model, the calibrated view vector of each pixel in each camera can be determined for the purpose of silhouette back projection. Figure 1 illustrates the silhouette extraction and 3-D reconstructed voxel person.

B. Body Sway during Standing

Body sway during standing includes sway in lateral and anterior-posterior directions. Body centroid (x_{ctr}, y_{ctr}, z_{ctr}) was estimated using the 3-D reconstructed voxel person described in the previous section. A fixed mid-point (x_{ref}, y_{ref}) was computed from the mean of centroid positions, and selected as a reference point on the ground plane for the base of support with z_{ref} = 0. The sway distance/amplitude is computed as the distance between the body centroid projection onto the ground plane and the reference point in 2-D space as:

$$d = \sqrt{\left(x_{ctr} - x_{ref}\right)^2 - \left(y_{ctr} - y_{ref}\right)^2} \qquad (1)$$

where x and y are the coordinate positions in the anterior-posterior (x) and lateral (y) directions (Figure 1c). Figure 2 illustrates a sway amplitude curve, where sway amplitude varies with time (frame number). As we are most interested in the maximum sway amplitude, a peak detection algorithm is applied to the curve. Usually, a curve smoothing technique is necessary prior to peak detection. Maximum sway location and frame are identified (red cross) in Figure 2.

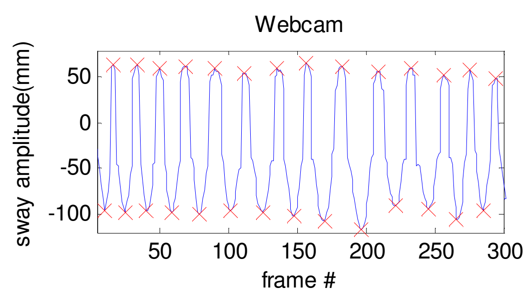

Fig.2 Sample sway amplitude curve during standing. Red crosses mark the maximum sway amplitude and time (frame).

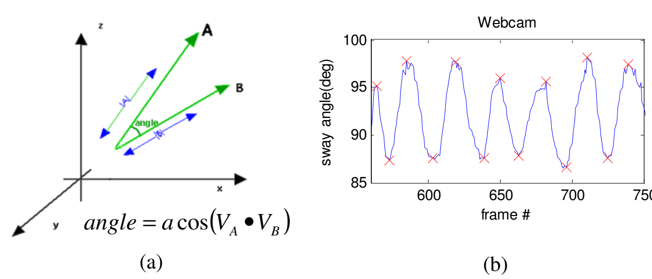

Fig.3 (a) Angle between 3-D vectors (b) Sample lateral sway angle during standing. Red crosses mark the maximum sway angle and time (frame).

In addition to the sway amplitude, we are also interested in the sway angle. The sway angle can be computed as the angle between two 3-D vectors, as seen in Figure 3(a). One vector is the axis connecting the body centroid and the base of support reference point (red line in Figure 1c), and the other vector is either the x-axis for anterior-posterior sway or the y-axis for lateral sway. Figure 3(b) illustrates the lateral sway angle computed with respect to the y-axis.

C. *Body Sway during Walking*

Body sway analysis during walking is more complicated compared to standing. Only lateral body sway can be analyzed due to the nature of the forward motion during walking. Figure 4(b) shows the trajectory of the body centroid extracted from voxel person during walking. First, peak sway centroid locations were identified, and a mid-point between the consecutive peak locations was computed. A linear interpolation is used to connect these mid-points and used as a line of progression. The sway amplitude is then calculated as the distance from each body centroid position to the line of progression. Figure 4 (a) is a sample voxel person during a walk, and (b) and (c) illustrate the 2-D body centroid trajectory and extracted sway amplitude during a sample walk.

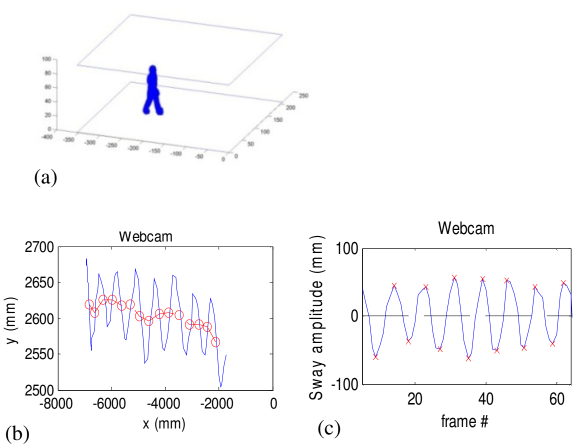

Fig. 4. (a) Voxel person during walking (b) Body centroid trajectory during walking projected onto 2-D space. (c) Sway amplitude in med-lateral direction. Red crosses mark the maximum sway angle and time (frame).

D. *Vicon Marker-Based Motion Capture for Ground Truth*

The three-dimensional motion analysis system, Vicon MX, allows for very accurate measurement of movement, using reflective markers and 7 high-speed cameras simultaneously. Markers were attached to subjects' feet, shoulders and back, and their 3-D positions were recorded by the Vicon system during the experiments. Body centroid locations and trajectory can be easily obtained through the back marker positions. A similar methodology as described in the previous sections is applied to extract the body sway parameters using body centroid information. Extracted sway parameters from the Vicon system are then used for validation purpose.

III. Validation Experiments

A. *Experimental Setup*

Two stationary cameras were placed in approximately orthogonal locations to record images while the subjects stood or walked. Unibrain Fire-i Digital Cameras were used for the experiments. The images were recorded at a frame rate of 5 frames per second, with an image resolution of 640x480 pixels. Markers were attached to subjects' feet, shoulders and back, and their 3-D positions were recorded by the Vicon system during the experiments. The body centroid location from the Vicon system was obtained as the back marker location, whereas the body centroid for voxel person was estimated as the mean of all voxel locations detected as part of voxel person for that frame. The sampling rate for the Vicon system in the experiment was 50 Hz.

Subjects participating in the test were volunteers from our research group. For the standing sway test, only one subject was tested. The subject stood in the middle of the lab, and performed anterior-posterior sway at a slow (approx. 13 cycles/min) then fast (approx. 17 cycles/min) speed for about 1 minute each, then lateral sway at a slow (approx. 11 cycles/min) then fast (approx. 20 cycles/min) for 1 minute each. For the sway during walk study, four subjects were tested with different walking patterns, including normal speed, slow speed, and limping. Subjects normally walked about 8-10 steps to complete the 16 ft walkway. But when different walking patterns were utilized, such as slow walks, the number of steps taken could be up to 16.

B. *Results*

i) Sway during standing

The body sway test results during standing are shown in Figure 5, and Tables I and II list the comparison differences between the webcam and Vicon systems.

The sway amplitude with respect to the mid fixed reference point is expressed in mm and shown in Figure 5(a), where red crosses mark the peak amplitude. We are most interested in the maximum sway amplitude during the sway process. The average sway amplitude (peak-peak) for anterior-posterior sway is 140.4 mm for the webcams vs. 154.1mm for the Vicon system. Looking at each individual sway cycle, the average difference between the two systems is 8.4%, with a standard deviation of 9.9. Similarly, for lateral sway, the average sway amplitude (peak-peak) is 140.4mm obtained from the webcams vs. 138.0 mm from the Vicon system. The average difference between the two systems for each sway cycle is 3.1% with a standard deviation of 5.1. Given the voxel resolution used in this experiment is 25.4mm (1 inch), the results extracted from the webcam voxel person matches with the Vicon results very well. Figure 5(a) also shows that the sway amplitude profile and frequency obtained from the web cameras closely follow those from the Vicon system. It clearly shows that there are 35 sway cycles in the anterior-posterior direction, and 30 cycles in the lateral directions. The reason that the anterior-posterior sway has a larger difference compared to the Vicon results than the lateral sway is believed to be related to the locations of the webcams with respect to the subject's location, which produces a larger reconstruction error in the anterior-posterior direction at the back of the person than the lateral direction. Voxel person reconstruction using fuzzy logic has been reported to reduce such reconstruction errors [20], and could be used for further improvement.

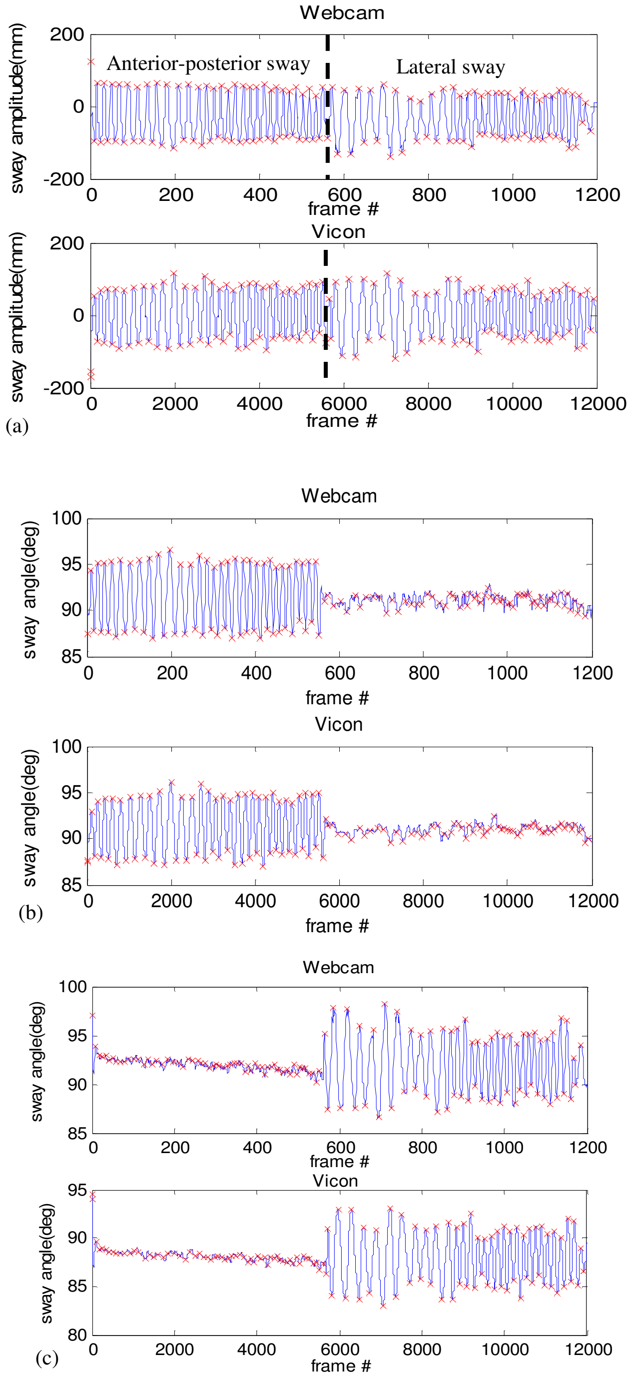

Fig. 5. Sway comparison during standing: Webcam vs. Vicon (a) Sway amplitude (b) Sway angle vs. X-axis: anterior-posterior sway (c) Sway angle vs. Y-axis: lateral sway

The sway angle results are shown in Fig. 5(b), (c), and Table II. As expected, the sway angles vs. x-axis (shown in Fig. 5b) for anterior-posterior sway shows clear oscillation signals around 90 degrees, and an almost constant signal for lateral sway. Similarly, the sway angles vs. y-axis (shown in Fig. 5c) for lateral sway shows clear oscillation signals around 90 degrees, and an almost constant signal for anterior-posterior sway. The average peak-peak sway angle computed from voxel person is 7.6 degrees in the anterior-posterior direction, and 7.0 degrees in the lateral direction, compared to 6.6 degree and 6.3 degree from the Vicon system, respectively.

Table I. Sway amplitude comparison (standing)

Avg. sway amplitude	Webcam (mm)	Vicon (mm)	Avg diff (%)	Max diff (%)	Stdev diff
A-p sway	140.4	154.1	8.4	16.7	9.9
Lateral sway	138.0	142.9	3.1	11.4	5.1

Table II. Sway angle comparison (standing)

Avg. sway angle	Webcam (deg)	Vicon (deg)	Avg diff (%)	Max diff (%)	Stdev diff
A-p sway	7.6	6.6	15.1	36.5	7.4
Lateral sway	7.0	6.3	11.4	32.9	6.8

ii) Sway during walking

Figure 6(a) overlays a 2-D trajectory of the body centroid for a walk from the webcam and the Vicon system respectively, and Figure 6(b) and (c) show the extracted lateral sway amplitude from them.

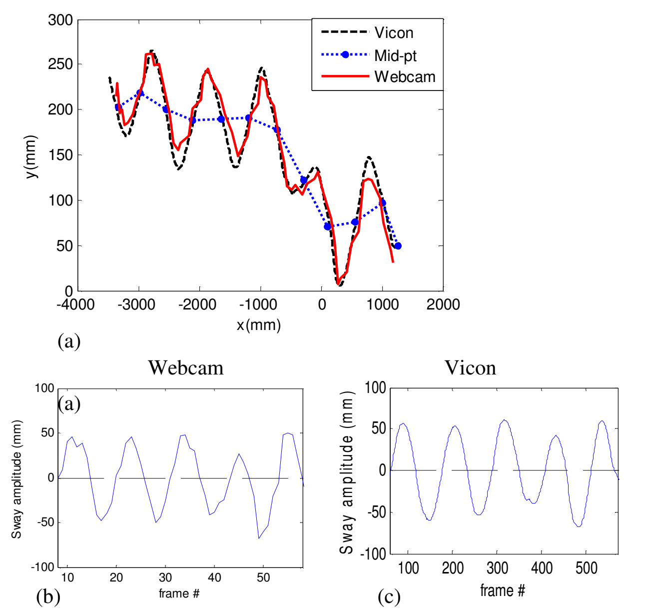

Fig. 6. Sway comparison during walking for ID2 slow walk (a) Body centroid 2-D trajectory: Webcam vs. Vicon (b) Webcam: sway amplitude (c) Vicon: sway amplitude

Table III shows the lateral peak-peak sway amplitude comparison while walking. We had selected only the experiment samples with a sway amplitude greater than or close to 50 mm (~2 inch). Below this threshold, the voxel person's resolution would not give meaningful results.

Through Table III, it has been observed that the webcam's sway amplitude results are consistently lower than those from the Vicon system. And the difference in terms of percentage is much larger compared to the standing case. This is because, for the standing case, the subject stands in the one optimal reconstruction location with respect to webcam locations, while for walking, the voxel person reconstruction error is much larger at boundary locations. In addition, in the standing case, there are many more sway cycles for analysis and with a larger sway amplitude compared to walking, which could eliminate some of the statistical errors and compensate for the lower webcam frame rate and voxel space resolution. Although the webcam results show seemingly large differences from the Vicon results, the differences are in fact all within the 1 inch (25.4mm) resolution limit, which leads us to believe that it is mainly due to a limitation from the voxel space resolution. Possible solutions include adding extra cameras and increasing camera frame rate and voxel space resolutions. Another alternative would be to use the fuzzy voxel person as a means of reducing reconstruction errors [20].

Table III. Sway amplitude comparison (walking)

	Webcam (mm)	Vicon (mm)		Webcam (mm)	Vicon (mm)
ID1			**ID2**		
slow	98.1	101.2	*normal*	53.3	65.2
limp	81.8	91.8	*slow*	93.7	109.5
ID3			**ID4**		
normal	65.1	74.0	*normal*	42.5	50.9
limp	61.1	79.9	*slow*	64.9	74.6

IV. SUMMARY

We have developed a body sway measurement system using low cost web cameras. The results have been validated with a marker-based Vicon motion capture system. Very good agreement was achieved for body sway during standing. Body sway measurement during walking is more challenging. Our web camera results have shown that the body centroid trajectory closely follows the Vicon results, but the sway amplitude has a larger error rate. It is believed to be related to the voxel person reconstruction error, and the voxel space resolution. Our future work will address these issues.

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