Automated Assessment of Postural Stability System

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Abstract — **The Balance Error Scoring System (BESS) is one of the most commonly used clinical tests to evaluate static postural stability deficits resulting from traumatic brain events and musculoskeletal injury. This test requires a trained operator to visually assess balance and give the subject a performance score based on the number of balance "errors" they committed. Despite being regularly used in several real-world situations, the BESS test is scored by clinician observation and is therefore (a) potentially susceptible to biased and inaccurate test scores and (b) cannot be administered in the absence of a trained provider. The purpose of this research is to develop, calibrate and field test a computerized version of the BESS test using low-cost commodity motion tracking technology. This 'Automated Assessment of Postural Stability' (AAPS) system will quantify balance control in field conditions. This research goal is to overcome the main limitations of both the commercially available motion capture systems and the standard BESS test. The AAPS system has been designed to be operated by a minimally trained user and it requires little set-up time with no sensor calibration necessary. These features make the proposed automated system a valuable balance assessment tool to be utilized in the field.**

I. Introduction

Traumatic Brain Injury (TBI) is defined as brain damage generated by an external mechanical force. Such forces can be caused by rapid acceleration or deceleration, blast waves, crush, or impact or penetration by a projectile. TBI can lead to temporary or permanent impairment of cognitive, physical and physiological functions. TBI contributes to a substantial number of deaths and permanent disability and it is a contributing factor to a third of all injury-related deaths in the United States. About 75% of TBIs that occur each year are concussions or other forms of mild traumatic brain injury (mTBI) [1]. TBI can cause a vast series of symptoms and it can be challenging to diagnose given the number of confounding factors involved. This is especially true for traumatic events that need to be diagnosed in the field, such as in military or athletic play scenarios [2].

Concussion diagnostic and management decisions are based on many elements, including symptom presentation, physical examinations and specialized tests designed to detect deficits resulting from concussive injuries [3]–[5]. Consequently, concussion assessment requires a multidisciplinary team of professionals and a series of specialized tests [6]. With the increased attention on and recognition of concussive injuries, there is a need for new assessment tools that, combined with more traditional techniques, will help evaluate concussion injuries more accurately [7], [8]. For some time, balance testing has been used in clinical settings as a reliable and valuable assessment tool to evaluate neurological functioning in subjects suffering from concussion and musculoskeletal injuries [9], [10]. There is a need to move concussion testing from the clinic onto the field, into the locker room, or out into the military theater [10], [11]. In these cases, computerized systems are often limited by size, weight, portability, ease of setup and use, and ease of calibration. Furthermore, there is a demonstrated need for such systems to be operable by non-medical or non-expert personnel, such as coaches and ordinary military corpsmen. We have developed a system that addresses these issues: a computerized system for administering and scoring the BESS test in a wide array of non-clinic locations using an inexpensive commodity motion-capture system.

II. Material and Methods

A. The BESS Test

The Balance Error Scoring System (BESS) is one of the most commonly used clinical tests for assessing postural stability following concussion [12]. It measures standing posture and balance related impairments [11]–[13]. Patients hold three different poses on two different surfaces (firm and foam), for 20 seconds each with their hands on hips and eyes closed. The three stances are: double leg stance with feet flat on testing surface; single leg stance, with the subject standing on the non-dominant leg with the contralateral limb held at approximately 20° of hip flexion, 45° of knee flexion; tandem stance, with one foot placed in front of the other with heel of the anterior foot touching the toe of the posterior foot. The subject's non-dominant leg is in the posterior position. A specially trained clinician observes the patient during each pose and records the number of balance "errors". These errors include:

- Moving the hands off the hips
- Opening the eyes
- Step, stumble or fall
- Abduction or flexion of the hip beyond 30°
- Lifting the forefoot or heel off the testing surface
- Remaining out of the proper testing position for longer than 5 seconds

Because the BESS test is scored by clinician observation, it is potentially susceptible to biased and inaccurate test scores that could lead to inappropriate return to duty or play before adequate recovery from the traumatic event [8]. The BESS is further limited by the need for properly trained clinicians to simultaneously administer, score and interpret the test and to ensure patient safety. Such an expert examiner may not be readily available in field situations. Finally, the BESS only focuses on static postural balance tasks and lacks assessment of more dynamic postural tasks. Testing only for static stability

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may not capture other important domains of balance, including dynamic or cognitive aspects [14].

B. *The Automated Assessment of Postural Stability System*

The purpose of this research is to develop, calibrate and field test an Automated Assessment of Postural Stability (AAPS) system to quantify balance control in military field conditions. The AAPS' objective is to evaluate postural and balance deficits due to concussion and musculoskeletal injuries commonly seen in active duty military personnel for return-to-duty assessment. The AAPS system has been developed in the C# programming language in the Microsoft Visual Studio 2015 programming environment and the .NET framework. The system includes a comprehensive graphical interface (GUI) to guide the operator and the subjects through the BESS test. It also provides user controls, data management features, a real-time display of the detected body and intuitive visual feedback on the AAPS tracking capabilities. Furthermore, the GUI has been designed to be user-friendly and its use only requires minimal training and experience. The current AAPS GUI is shown in Fig. 1.

C. *System Design*

The AAPS system utilizes an inexpensive Microsoft Kinect v2.0 motion capture sensor [15], [16] and a custom designed software suite for Microsoft Windows to objectively track kinemtics during the Balance Error Scoring System (BESS) test. Fig.2 displays the system workflow. Set-up time is minimal, and no additional calibration time is required. These features make the AAPS a valuable balance assessment tool to be utilized in the field. It only requires the patient to assume the right stance and the system starts extracting tracking information from the sensor data stream and uses a GUI to display the tracked skeleton. By using some simple visual feedback features, the system provides the user with information regarding the subject's position, joints and eyes detection. This helps the non-trained user in positioning the subject for the test and guarantees that all the necessary parameters are tracked correctly before starting the test. During the test, in each frame, the AAPS extracts two types of data from the Kinect sensor: infrared camera videos, which will be saved in the computer memory for optional off-line analysis; and the subject's joint location and eye data. These will be used, frame-by-frame, to build arrays containing the three metrics that will be then used to evaluate errors, namely relative joint distances, segment angles and eye state. After test completion, these metrics will be used to compute balance errors as explained in more detail in the next section.

III. AAPS Balance Error Assessment

Once the subject is in position, the test is started and the AAPS guides the user through the set of six stances and then automatically computes balance errors. The AAPS does not require baseline recordings for balance assessment. It only uses a few seconds worth of calibration data that are acquired right before the start of each BESS stance, with the patient standing still in the right test position. The calibration data are used to learn subject dependent features, such as body shape and postural characteristics. Furthermore, calibration data are necessary to compensate for any small fluctuations in joint tracking that may occur. This is necessary, since even when a subject stands as still as possible, the Kinect typically shows joint locations fluctuating to some small degree. In order to not erroneously flag such flutter as balance errors, a brief calibration recording is used to determine the mean and standard deviation of each joint location. During actual testing, only movements exceeding five standard deviations are flagged as balance errors. In order to detect a subject's postural changes, three biometric measurements are used: joint distances, segment angles and eye status. These variables are computed in each video frame but error detection is performed on the output of a moving average filter with a window time duration of five frames. This filter was implemented to further stabilize the system error detection by reducing high frequency artifacts. The average of these metrics during calibration are compared to their corresponding actual values during testing to detect changes in postural stability. Equation 1 shows how the average distance calibration values are computed.

$$\hat{d}_{cal} = \frac{1}{N_{cal}} \sum_{fr=1}^{N_{cal}} \sqrt{\left(joint_{1_x}(fr) - joint_{2_x}(fr)\right)^2 + (joint_{1y}(fr) - joint_{2y}(fr))^2} \quad (1)$$

Equation 1 provides one calibration value for each biometric variable used. N_{cal} is the number of calibration frames used, fr is the frame index, and $joint_{1_x}$ and $joint_{1y}$ are the 2-D coordinates of a joint of interest.

After calibration, during postural testing, the metric variables are computed once per frame and the resulting

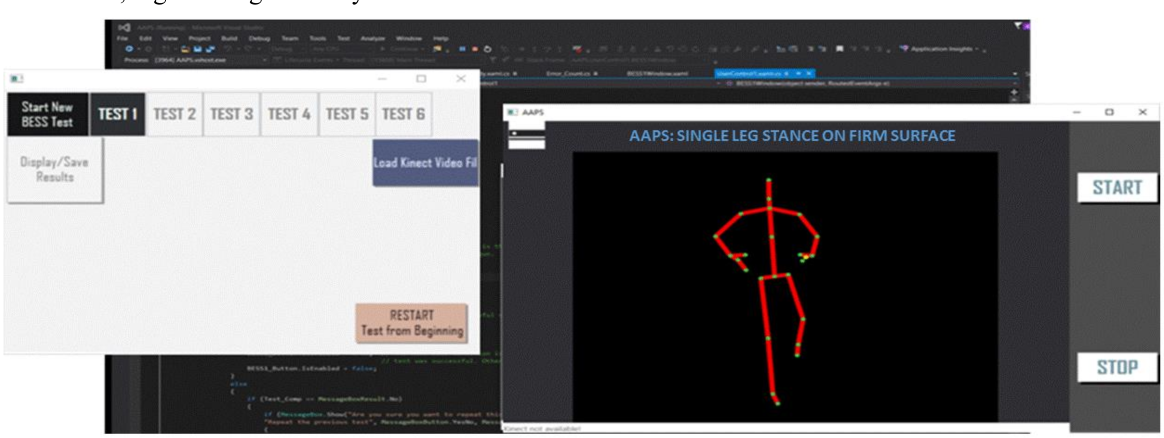


Figure 1: The AAPS Graphical User Interface

sequences $\{d_{fr}\}_{fr=1}^{N}$ stored in memory arrays (See Equation 2). Error calculation is performed by comparing the average calibration values to the output of a moving average filter with a sliding window duration of five frames (see Equation 3).

Sequence: $\{d_{fr}\}_{fr=1}^{N}$ where fr is the video frame index

$$d_{fr} = \sqrt{\begin{matrix}\left(joint_{1_x}(fr) - joint_{2_x}(fr)\right)^2 + \\ (joint_{1y}(fr) - joint_{2y}(fr))^2\end{matrix}} \tag{2}$$

where $\{\hat{d}_i\}_{i=1}^{N-n+1}$ is the moving average output window, where n is the number of frames in the moving average (default is 5).

$$\hat{d}_i = \frac{1}{n}\sum_{fr=1}^{1+n-1} d_{fr} \tag{3}$$

If the changes in distances and angles between the calibration and the actual values are larger than five times the standard deviation in the calibration data, then the AAPS system will detect an error. The error detection criterion is shown in Equation 4.

$$e_i = \left|\hat{d}_i - \hat{d}_{cal}\right| > 5 * \sigma_{cal} \tag{4}$$

where

$$\sigma_{cal} = \sqrt{\frac{1}{N_{cal}}\sum_{fr=1}^{N_{cal}}(d_{fr} - \hat{d}_{cal})^2} \tag{5}$$

At the end of a complete BESS test, the errors with respect to each condition and the error types are stored in a file together with patient, test information and video files corresponding to the scored tests.

The automated system's BESS scoring is based on the detection of four types of errors that are generated when: 1) the hands are off the hips; 2) the foot distance changes; 3) the angle between the center of the shoulders and the center of the hips becomes larger than 30°; 4) the subjects open their eyes.

IV. MAIN CHALLENGES OF A KINECT-BASED AUTOMATED BALANCE SYSTEM

As a motion tracking system, the Kinect sensor has some clear limitations as compared to professional or clinical grade digital motion capture systems that make use of more sophisticated sensors and body markers. In this section, some of the main challenges are introduced:

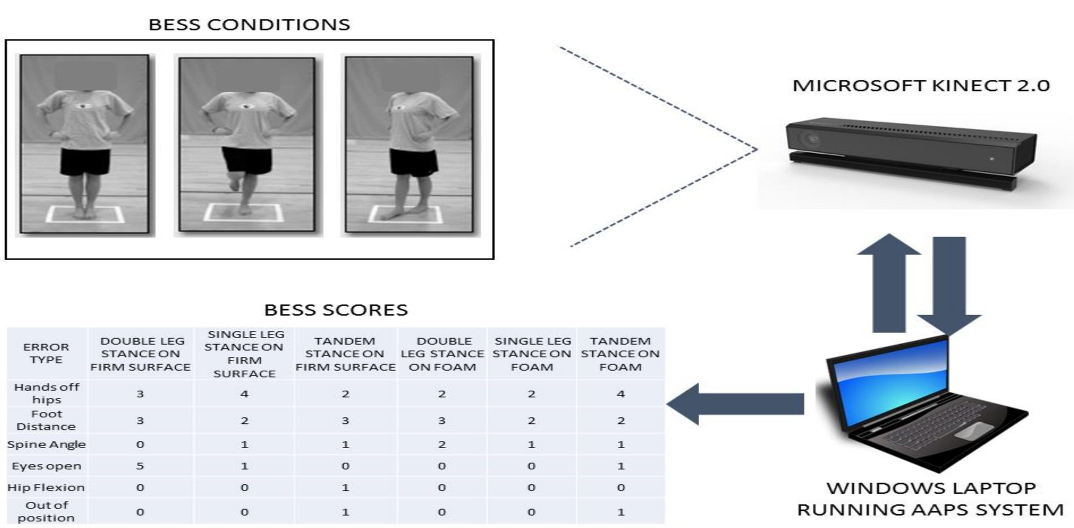
1) The Kinect sensor cannot stably detect foot positions on certain surfaces, especially during static testing. This is likely caused when the floor interferes with the infrared depth signal projected by the Kinect. This issue is being addressed by determining the optimal sensor height, angle, and distance from subject.

2) The Kinect sensor can successfully detect subject's trunk lateral movements from the vertical position, in the frontal plane. However, the sensor is not as effective when tracking trunk changes that occur in the transverse plane. The AAPS will account for this limitation by combining other joint positions to estimate 3-dimensional trunk movements.

3) During the Tandem Stance, with the subject facing the Kinect, the sensor and the body tracking system have issues detecting the back leg that is hidden behind the other leg. Even though the information on the back leg is not available to the AAPS, our system will infer changes in the back leg position by using data derived from other joints.

4) The eye gaze sensor tracking capabilities yield the best results when the subject's eyes are aligned with the sensor's color camera. This can be challenging when the sensor is placed at the height of the subject's trunk. This issue can be solved by performing a series of face orientation computations to guarantee maximal eye detection accuracy during the test.

An important implementation detail relates to the Kinect sensor, which provides a number of different data streams, such as both infrared and color videos, depth information, tracking data, and gesture and face recognition. These data require intensive real-time signal and image processing that is carried out on the computer video card using Microsoft proprietary algorithms. While the real-time data are valuable for the AAPS to perform accurately, the resulting computational burden makes the system performance unpredictable and unstable. A performance bottle neck arises as the computer handles this Kinect data in real-time while simultaneously running other system processes. Microsoft's



ERROR TYPE	DOUBLE LEG STANCE ON FIRM SURFACE	SINGLE LEG STANCE ON FIRM SURFACE	TANDEM STANCE ON FIRM SURFACE	DOUBLE LEG STANCE ON FOAM	SINGLE LEG STANCE ON FOAM	TANDEM STANCE ON FOAM
Hands off hips	3	4	2	2	2	4
Foot Distance	3	2	3	3	2	2
Spine Angle	0	1	1	2	1	1
Eyes open	5	1	0	0	0	1
Hip Flexion	0	0	1	0	0	0
Out of position	0	0	1	0	0	1

Figure 2: The AAPS operational diagram

Kinect libraries respond to limitations in computing power by automatically reducing the amount of information coming in from the various Kinect sensors by continually adjusting the framerate during run-time. In ideal conditions, the sensor returns data streams at 30 frames/second. However, during our testing, it was not unusual to see the frame rate drop below 10 frames/second, even though the AAPS was tested on high-end laptops with late model quad-core processors and dedicated video cards. In order to account for this variability in frame rate, the AAPS is implemented using a series of timer variables that allow it to keep track of real-time system performance. Furthermore, the variable and non-controllable frame rate will affect the operation of the moving average, the filter time constant will depend on the frame rate. To compensate for such variability, the moving average size can be chosen dynamically and adapted to the instantaneous frame rate to keep the filter cut-off frequency constant. The system real-time performance does not appear to be a main concern when performing static testing, but may become critical in the future when implementing dynamic balance testing.

V. FUTURE WORK

In future work, the AAPS system will be further expanded to introduce new functionalities. Namely, the AAPS will not only perform the BESS test, but it will also provide kinematic metrics that will better capture the examinee's balance deficits by using time measures of performance and dynamic testing of performance during fundamental movements. Furthermore, the AAPS software suite will be expanded by integrating physiological data recorded from the examinee in real time, into the concussion battery of tests, while performing the automated tests. These data will be used to create personalized test scoring procedures and thus increase the system capability to evaluate cognitive and behavioral elements of the examinee. Moreover, assessing the examinee's physical engagement and states will greatly improve the AAPS ability to account for suboptimal effort levels, that is a major concern in computer-based testing for concussion assessment [10].

VI. CONCLUSION

The proposed research presents an automated system for quantifying balance control deficits due to traumatic brain injury. The AAPS system consists of two components: a Microsoft Kinect motion sensor and a Windows laptop running a specifically developed software suite. The AAPS main goal is to perform the BESS test in filed conditions, with no prior calibration and no medical or experienced personnel needed. The AAPS provides reliable and repeatable balance assessment results that are important in managing the return to duty determination after traumatic brain events.

This work has been demonstrated the validity of the AAPS for performing automated BESS tests. In this view, the set-up simplicity, robustness, test repeatability and the user-friendly approach of the AAPS make the system the perfect platform to develop the next generation of in the field concussion evaluation tests.

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