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Development and Validation of a Clinic Based Balance Assessment Technology

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Abstract — **Falls in the elderly are a major problem worldwide, with enormous associated societal costs. Deficits in balance and postural control have long been associated with falls risk in elderly adults. The gold standard for quantitative assessment of human balance in a clinical setting is the force plate which is highly expensive, non-portable and requires specialized personnel to operate. The present study aims to evaluate the validity and reliability of a portable quantitative balance measurement technology compared to the forceplate. Two participants (1 male, 1 female) performed sixteen balance trials each (eight eyes open and eight eyes closed). Simultaneous data were recorded from a portable pressure sensor platform and a laboratory grade force platform. Standard centre of pressure (COP) metrics from both modalities were compared and high levels of agreement in terms of intraclass correlation coefficient (ICC), mean absolute error (MAE) and mean percentage error (MPE) were found.**

I. Introduction

The world's population is ageing and this trend is set to increase dramatically in the next 100 years. This impending demographic shift will be most acute in North America, Europe and Japan, placing an enormous burden on healthcare systems. Modern technological approaches may facilitate more efficient delivery of healthcare. A move towards ambient, distributed and pervasive technologies to deliver healthcare more efficiently is proposed as a means of reducing the strain on traditional hospital based healthcare delivery systems. This will increase the quality of life and independence of all patients, especially elders and those with chronic illnesses, and also serve to reduce the costs inherent in the current hospital-centric system. This will reduce the number of preventable visits to health-care professionals, provide accurate, reliable and useful clinical information and efficiently synchronise to electronic health records complimenting current health-care provision.

Falls in the elderly are a major problem worldwide, and can lead to serious injury, hospitalisation, restricted mobility, and institutionalisation [1]. The cost of falls each year, among elderly people in the U.S. alone, has been estimated to be in the region of U.S. $20 billion [2]. Deficits in postural stability and balance have long been associated with falls in older adults [3]. An impaired stability when standing and slow voluntary stepping, have also been shown to be associated with falls [4]. Common methods of falls risk assessment, including the Berg Balance Scale and the Timed Up and Go (TUG) test, are clinic based, variable in administration and require specialised clinical staff. Alternative quantitative technologies for falls risk assessment, suitable for deployment in hospital and community clinics as well as in the home, are currently under development [5,6]. Such advances need to be objective, repeatable and easily measured by a non-expert user. In a review, Melzer et al. [7] describes five studies which associates falls with various force platform measures, primarily metrics derived from variations in the centre of pressure. However, the modality used, force platforms, are difficult to install making them unsuitable as a clinic-based modality for falls risk assessment.

This paper describes the development of a portable quantitative balance assessment system suitable for clinic and home based assessment. The system consists of a novel pressure sensor and two novel algorithms for calculation of COP estimates from the pressure sensor data. The system is compared against a laboratory-grade force plate (the gold standard for quantitative balance assessment) using multiple trials from two subjects. System validity was evaluated through measurement of COP during a series of standing balance trials.

II. Methods

A. Hardware

1) Forceplate

Data were collected at a rate of 1kHz from AMTI (Advanced Mechanical Technology Inc.) force plates. The centre of pressure (COP) was calculated using four strain gages placed at the four corners of the platform and was calculated for each frame of data. Data were collected using the CODA motion analysis software (Charnwood Dynamics, UK).

2) Pressure sensor platform

Pressure sensor data was obtained using a Tactex high density (HD) pressure sensor mat (Tactex Controls Inc.,

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Victoria, Canada). The sensor measures 915x61mm and contains an array of evenly distributed grid of 72x48 pressure sensors (tactels). Each tactel is sensitive to pressure and has a high resolution. Data were collected using a custom BioMOBIUS interface (BioMOBIUS, Dublin, Ireland, www.biomobius.org) using a Dell Precision M90 laptop. For each sample of data collected, a frame of data described the current pressure applied to the pressure sensing grid. The X and Y coordinates of the Tactex HD mat were converted to metric. Changes in tactel values, from a change in the force applied to the pressure sensing grid, resulted in an update to the matrix describing the current state of the mat. The matrix which reflects the current pressure applied to the mat was updated in windows of 200 successive changes. This resulted in a non-uniform sampling rate. Upon periods of movement this resulted in good time resolution. Between updates, the pressure applied to the sensor remained constant. A sample and hold algorithm was used to resample this data resulting in an effective constant sampling rate of 10Hz.

3) Data Collection Synchronisation

The pressure sensor data acquisition system and the forceplate systems were synchronized using a dedicated trigger output connected to wireless sensor (SHIMMER, SHIMMER Research, Dublin, Ireland) and relayed via Bluetooth. Data from the synchronization and pressure sensor devices were simultaneously recorded within BioMOBIUS [8,9].

B. Experimental Protocol

Sixteen balance tests (8 eyes open and 8 eyes closed) were recorded from each of two healthy adults, 1 male (29 years old, 80Kg) and 1 female (22 years old, 50Kg). Data were recorded with each subject standing still and facing in the same direction. Data were collected simultaneously from the balance measurement system and from a force plate. The pressure sensor platform was placed flush on top of the force plate and the subject was requested to stand on top of the pressure sensor. The position of the sensor was investigated to ensure it did not dampen the sensitivity of the forceplate. Each test lasted approximately 60s, the first and last 15s of each trial were neglected from analysis leaving 30s of data per trial. There were 60-120s rest between tests. The participant remained in a comfortable stance for the duration of each trial with their gaze fixed forward and their arms held by their side (see Figure 1).

C. Derivation of Tactex HD Mat COP

Two algorithms were developed to estimate centre of pressure based on the contact area between the pressure sensing platform and feet of the subject. An empirically defined threshold was used to define the 'active tactels' upon which pressure was applied. During data collection, this pertained to the feet of the participant (see Figure 1).

1) Centre of all 'active' tactels (CAAT)

The absolute centre of all active tactels per frame of data collected was used as to estimate COP location for each time sample, this was used to generate a time-series of COP excursions over the course of each balance trial.

2) Centroid of the heels and toes (CHAT)

The overall centre of the four heel and toe points was defined as the centroid of the heels and toes (CHAT) and was used as an additional estimate of the COP location for a given data frame. An algorithm was developed to localise the heel and toe points for each foot. Firstly, each frame was scanned horizontally from left to right across the feet. The first active tactels registering pressure were defined as the outer edge of the left foot. The foot was empirically defined to have a maximum width of 8 tactels (10.1 cm), after which the inner edge of the right foot was subsequently scanned for. As the subjects faced a pre-defined direction, each foot print was broken into two sections: heel and toe. The centres of each of these areas were defined as the each heel and toe points respectively.

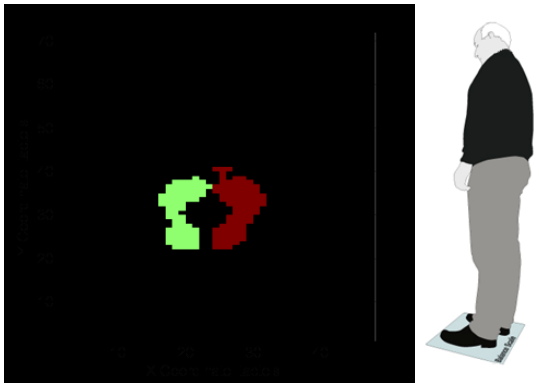

Figure 1: (Left panel) Sample data for one frame of data obtained from pressure sensing platform during quiet standing balance trial (left and right feet visible). (Right panel) typical stance during

D. Derivation of standard COP-based Measures

Standard COP measures [10] were extracted from force plate and using both pressure sensor methods for COP estimation over the 30s balance trial. The following parameters were calculated:

1) The mean distance between each COP point and the mean COP point (MDIST):

$\overline{AP} = \frac{1}{N}\sum APo[n]$, $\overline{ML} = \frac{1}{N}\sum MLo[n]$ where APo and MLo are the antero-posterior and medio-lateral time series coordinates of the COP and $\overline{AP}$ and $\overline{ML}$ are the mean antero-posterior and medio-lateral COP coordinates over the recording period.

$AP[n] = APo[n] - \overline{AP}$, $ML[n] = MLo[n] - \overline{ML}$

where AP and ML are COP coordinates relative to the mean COP.

$RD[n] = (AP[n]^2 + ML[n]^2)^{1/2}$ n=1, 2, ..., N

where the resultant distance RD is the Euclidian distance from each set of coordinates to the mean COP point.

$$MDIST = \frac{1}{N}\sum RD[n] \quad (1)$$

where MDIST is the mean distance of the RD times series.

2) The root-mean-squared distance between each COP point and the mean COP point (RDIST):

$$RDIST = \left[\frac{1}{N} \sum RD[n]^2 \right]^{1/2} \quad (2)$$

where RDIST is the root-mean-squared distance of the RD times series.

3) The total COP path length travelled over the recording period (TOTEX):

$$Diff\_AP(n) = AP(n+1) - AP(n)$$
$$Diff\_ML(n) = ML(n+1) - ML(n)$$
$$TOTEX = \sum_{n=1}^{N-1} \left(Diff\_AP(n)^2 + Diff\_ML(n)^2 \right)^{1/2} \quad (3)$$

where total excursions (TOTEX) is the total length of the COP path.

4) The average velocity of the COP (MVELO):

$$MVELO = TOTEX / T \quad (4)$$

where MVELO is the mean velocity of the COP over the duration of data collection (T).

E. Statistical Analysis

The pressure sensor was aligned flush to the surface of the force plate, to ensure all downward pressure applied was directly transferred to the force plate. A number of comparative metrics, including the intraclass correlation coefficient (ICC) of the type (2,k) as defined by Shrout and Fleiss [11], the absolute error (AE), mean absolute error (MAE), mean squared error (MSE), mean percentage error (MPE) and Pearson's Correlation (r) were used to examine the performance of the portable quantitative balance system compared to the forceplate. All COP metrics were normalised to vary between 0 and 1 prior to analysis.

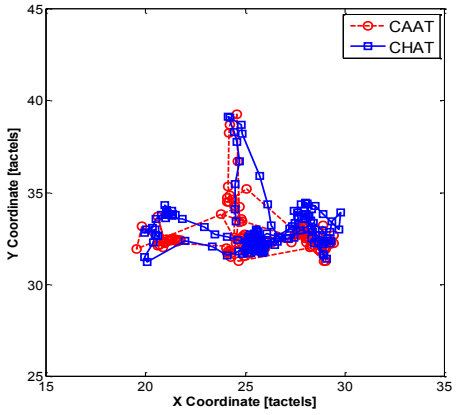

Figure 2: Centre of pressure excursion obtained using CAAT and CHAT algorithms for a healthy control subject performing standing balance trial under eyes open

III. Results

A. Validity of quantitative balance system

High levels of agreement rates between the quantitative balance system and the forceplate were observed for a number of COP measures. The data for each metric was normalised to a maximum value of one. A comparison of the COP mean distance metrics from the quantitative balance system and the force plate is shown in Figures 3 and 4. The data is split between each condition, eyes open (EO) and eyes closed (EC), for both subjects in these figures.

TABLE I.
LEVELS OF AGREEMENT RATES FOR THE COMPARISON BETWEEN THE COP MEASURES DERIVED FROM THE TACTEX HD MAT AND THE FORCEPLATE.

Measure	COP Algorithm	ICC^	MAE	MPE (%)	MSE	r*
MDIST	CAAT	0.952	0.072	16.74	0.007	0.95
	CHAT	0.817	0.160	35.73	0.033	0.82
RDIST	CAAT	0.951	0.073	15.99	0.008	0.95
	CHAT	0.820	0.166	35.44	0.034	0.83
TOTEX	CAAT	0.761	0.206	41.26	0.050	0.93
	CHAT	0.620	0.299	59.72	0.105	0.88
MVELO	CAAT	0.760	0.206	41.32	0.050	0.93
	CHAT	0.620	0.300	59.76	0.105	0.88

*p-value <0.001
^ ICC (2,k)

Significant increases ($p < 0.01$) were found for subject 1 during the eyes closed condition for COP mean distance (measured by the force plate) as seen in Figure 4. No significant difference was found between both conditions for subject 2.

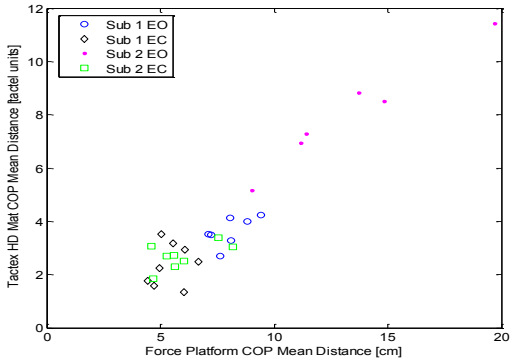

Figure 3 Comparison of Force platform and CAAT (obtained using pressure sensor platform) COP mean distance for both Subjects and Eyes Open (EO) and Eyes Closed (EC) conditions.

IV. Discussion

It was found that of the two pressure sensor derived COP metrics CAAT consistently outperformed CHAT in measuring common COP measures. The CAAT algorithm does not account for the shape of each foot, but only the

contact area between the outer edges of both feet and the pressure sensor platform.

For both CHAT and CAAT, it is the change in the contact area between the feet and the pressure sensor platform which is related to the balance metrics. However, variations in the distribution of pressure without a concomitant change in the contact area between the pressure sensor platform and the feet are possible. This would result in a reduced efficacy in the balance assessment of pressure sensor platform. However, a close relationship between the change in the contact area of the feet and the variation of COP has been found. This high agreement is likely due to changes in the distribution of pressure on the feet resulting in a change in the contact area between the foot and the mat.

For this validation study, data were collected over multiple trials on this small cohort. Data are currently being collected from a larger cohort of older adults over multiple trials in order to assess variations in balance and postural stability. The current algorithm uses thresholding to distinguish the foot print of the participant. This is directly affected by the weight of the subjects and was defined empirically. Further analysis will assess how variations in the weight of participants affect the detection of foot prints.

A window of 200 changes to the tactel values must be filled before a new frame of data, representing the current pressure applied, is produced. The resulting sampling is not constant. Alternative methods of data collection producing a uniform sampling rate are under investigation.

V. Conclusion

This paper discusses the development of novel, portable, low-cost system and algorithms for quantitative assessment of balance and postural control. Two novel algorithms for calculation of centre of pressure and novel pressure sensor platform are discussed. High rates of agreement were found upon comparing this technology to a laboratory grade forceplate (the gold standard for quantitative balance assessment). This system may be suitable for deployment in a clinical or community care settings. Further studies will employ this technology in the development of community and primary care based falls risk assessments for community dwelling older adults.

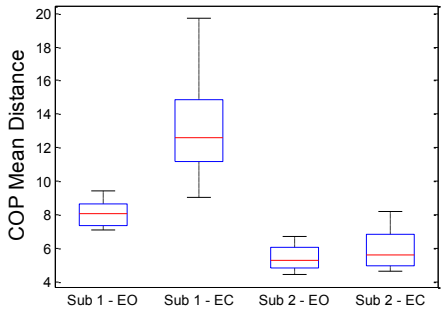

Figure 4: COP mean distance over each trial for both subjects over both eyes open (EO) and eyes closed (EC) conditions.

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