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Body-worn sensor based surrogates of minimum ground clearance in elderly fallers and controls

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***Abstract*—Falls in the elderly are a major problem worldwide with enormous associated economic and societal costs. Minimum ground clearance (MGC) is an important gait variable when considering trip-related falls risk. This study aimed to investigate the clinical relevance of inertial sensor derived parameters, previously shown to be related to MGC. Previous research by the authors reported a surrogate method for assessing minimum ground clearance (MGC) using shank-mounted inertial sensors in young controls. The present study tests this method on a cohort of 114 community dwelling elderly adults, with and without a history of falls, completing a 30m continuous walk. Parameters based on the shank angular velocity signals that were shown to be associated with MGC showed significant differences (p<0.05) between fallers and non-fallers yet did not correlate strongly (r<0.7) with two standard measures of falls risk (TUG & BBS). Weak correlations were observed between the angular velocity derived parameters and gait velocity. We conclude that these parameters are clinically meaningful and therefore may constitute a new measure of falls risk.**

I. Introduction

The potential for the use of body-worn inertial sensors as a low-cost, light-weight tool for extra-laboratory gait monitoring is well recognised. However, the potential clinical value of the large quantities of data that can be generated using these devices has yet to be fully exploited. One area in which body worn sensors may have particular clinical relevance is in measurement of minimum ground clearance (MGC), the local minimum distance between the foot/shoe and the ground during the swing phase of walking. At this critical instant, the foot is at or near its maximum velocity, the body is in single limb stance with the centre of mass outside the base of support and in the direction of progression [1]. MGC is a particularly important gait variable when considering trip-related falls in the elderly. There is evidence to suggest that properties of MGC are altered in older adults, and in those at risk of falls [2, 3].

A recent study by the present authors demonstrated an association between angular velocity variables measured using a shank-mounted inertial sensor during a timed up and go (TUG) test, and falls history in a cohort of 349 older adults [4]. The authors hypothesised that these variables may be related to MGC. A subsequent validation study on a younger cohort demonstrated that mean and coefficient of variation of minimum ground clearance (MGC) during walking could be estimated using statistical models based on mean absolute valued angular velocity about an axis perpendicular to the sagittal plane (SagAngVel) recorded using a gyroscope attached to the foot and shank [5] (Figure 1).

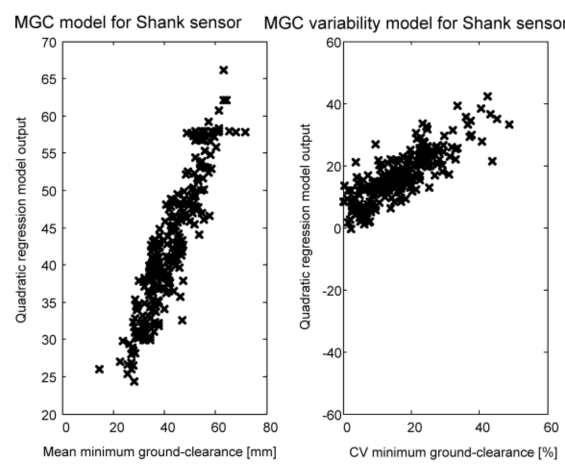

Figure 1: Comparison of the output from quadratic regression models of mean and CV MGC to actual MGC values based on variables derived from the shank angular velocity signals obtained from young control subjects performing over-ground walking trials.

Consecutive steps of steady-state walking are required for accurate measurement of MGC statistics. This is usually achieved through the use of treadmills and optical marker-based motion capture systems, sometimes

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combined with intelligent gait analysis systems [3, 6]. However, treadmill walking, by its nature, imposes a certain rhythm on the gait of an individual, and may not be completely representative of a subjects' true gait. Test protocols that are based on measurement of MGC in a more natural context would be clinically beneficial. The premise underpinning the present study suggests that if MGC is related to inertial sensor derived variables, these variables may then be used to meaningfully analyze the trip-related falls risk of elderly individuals as they move about a natural environment. The aim of this study was therefore to extend previous work by testing the ability of SagAngVel based parameters to differentiate a cohort of fallers and non-fallers performing a 30m steady-state walk in an extra-laboratory environment.

II. METHOD

A. Participants

The gait of 114 (38 males, 76 females, mean age 71.0±6.6 years) community dwelling older adults was evaluated (TRIL clinic, St James' hospital, Dublin, Ireland). This study was conducted as part of a larger study on ageing (www.trilcentre.org). The inclusion criteria were persons aged 60 and over, able to walk independently with or without aid, and able to provide informed consent. Ethical approval was received from the St. James hospital ethics committee. 54 participants (fallers) had a history of falls in the previous 5 years while 60 did not (non-fallers).

B. Study Protocol

Inertial sensor data were acquired using two body-worn sensors (SHIMMER, Shimmer research, Dublin, Ireland) [7], while participants walked at a self-selected normal walking speed along a straight corridor for a distance of 30m. Sensors were attached to the mid-point of the anterior shank by means of elasticized bandages, oriented to capture movement in the anatomical sagittal plane (gyroscope sensor Y-axes, Figure 2).

Each participant was also evaluated using two standard clinical methods for assessing falls risk: the Berg balance scale (BBS) [8] and the timed up and go test [9] (the time taken to complete the TUG test, known as the manual TUG, was recorded using a stopwatch).

C. Data Collection

Inertial sensors contained both a tri-axial accelerometer and an add-on tri-axial gyroscope board. Inertial sensor data, sampled at 102.4 Hz, were acquired in real-time and transmitted wirelessly via Bluetooth to a custom developed BioMOBIUS application (www.biomobius.org (Dublin, Ireland)). The data were then exported to text format for subsequent offline analysis. All post processing and analysis was carried out offline using Matlab version 7.11 (www.mathworks.com (Natick, VA, USA)).

The raw gyroscope data were calibrated using a standard calibration procedure [10]. Before further processing, the raw signal from each sensor was low pass filtered with zero-phase 4th order Butterworth filter with a 10Hz corner frequency.

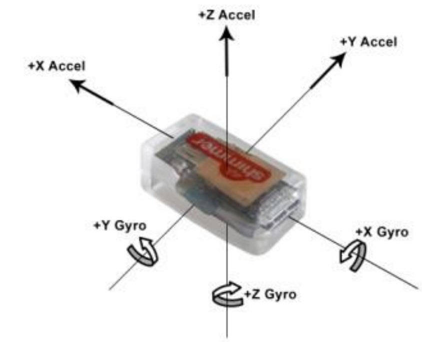

Figure 2: Sensor coordinate axes: X gyro axis: measures movement about the plane perpendicular to the long line of the shank; Y gyro axis: measures movement in the sagittal plane; Z gyro axis: measures movement in the plane the long line of the shank lies in.

D. Estimating MGC from shank angular velocity signal

In a previous study, we discussed a method for estimating MGC using angular velocity [5] derived from shank mounted gyroscopes. A number of measures were calculated from the filtered angular velocity signals measured over an entire walking trial, and used to generate regression models of mean and coefficient of variation (CV) MGC. This method was applied to the present data set. The following parameters were derived from the left and right shank angular velocity signals from each walking trial, for each participant:

- Mean absolute value
- Maximum
- Minimum
- Mean value at mid-swing points
- Coefficient of variation

Mid-swing points were calculated for each walking trial using a previously reported method [11]. In addition, a previously reported method was used to obtain a measure of the gait velocity for each walking trial [12].

E. Angular Velocity parameters from 30m walk data

Each parameter discussed above was derived from the shank angular velocity in the sagittal plane (SagAngVel) for each corridor walking trial in order to determine if there were significant differences between fallers and non-fallers in the shank angular velocity variables. Figure 3 shows a sample of the SagAngVel signal from a 63 year old female participant performing the 30m walk.

F. Statistical analysis

The Mann-Whitney version of the Wilcoxon rank sum was used to test for significant differences between fallers and non-fallers in gait velocity and in the derived SagAngVel variables which have previously shown association with mean and CV MGC [5]. Pearson's correlation coefficient was used to examine how well each SagAngVel value correlated with the BBS score and the manual TUG time. Additionally, Pearson's correlation coefficient was also used to examine the strength of the relationship between gait velocity and each SagAngVel variable. The squared correlation coefficient (R^2) was used to examine the proportion of variability in gait velocity that could be explained by each SagAngVel measure.

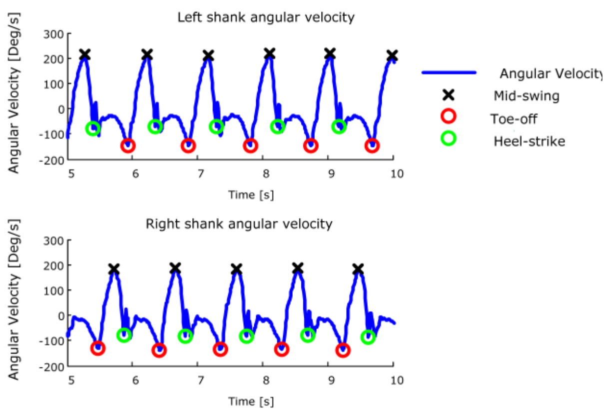

Figure 3: Sample of the SagAngVel signals obtained from body-worn gyroscopes (Y gyroscope axis) mounted on the left and right shanks from a 63 year old female participant performing the corridor walk.

III. RESULTS

A. *SagAngVel parameters derived from 30m walk*

Three parameters derived from SagAngVel showed significant discrimination between fallers and non-fallers ($p<0.05$): mean SagAngVel at mid-swing points, mean absolute valued SagAngVel and min SagAngVel. Results are tabulated in Table 1. Fig. 4 shows a histogram of the mean absolute SagAngVel for fallers and non-fallers.

TABLE I: SAGANGVEL (ANGULAR VELOCITY ABOUT AN AXIS PERPENDICULAR TO SAGITTAL PLANE) DERIVED PARAMETERS. PARAMETERS SHOWING SIGNIFICANT DISCRIMINATION (P<0.05) BETWEEN FALLERS AND NON-FALLERS ARE INDICATED WITH ^ AND HIGHLIGHTED IN BOLD. CORRELATION OF EACH PARAMETER WITH THE MANUAL TUG (R MTUG) AND BERG BALANCE SCALE (R BBS) ARE SHOWN

Variable	Faller (mean±std)	Non-faller (mean±std)	r BBS	r mTUG
Mean SagAngVel mid swing^ (deg/s)	167.16±29.63	182.28±19.93	0.58	-0.63
Mean abs. SagAngVel. ^ (deg/s)	56.10±12.26	61.60±7.54	0.57	-0.60
Min SagAngVel^ (deg/s)	-125.28±24.94	-136.11±21.99	-0.44	0.53
Max SagAngVel (deg/s)	199.01±33.16	211.91±29.46	0.41	-0.49
CV SagAngVel (%)	84.82±13.04	82.35±5.52	-0.25	0.21

B. *Relationship with Gait velocity*

No statistically significant difference (p=0.09) in gait velocity was observed between fallers (131.20±30.37 cm/s) and non-fallers (143.17±19.82 cm/s). R^2 values indicate that between 1-23% of the variability observed in the SagAngVel derived parameters can be explained by differences in gait velocity, suggesting a weak association between the two constructs, as shown in Table II.

IV. DISCUSSION

This study utilized shank-mounted inertial sensor derived angular velocity parameters, previously shown to be related to MGC [5], to successfully distinguish fallers from non-fallers during an unconstrained 30m walk. This is an important finding that suggests that these parameters are clinically meaningful and may therefore be of use in screening for falls risk, or in long-term ambulatory monitoring of gait.

TABLE II: PEARSON CORRELATION COEFFICIENT (R) OF EACH SAGANGVEL PARAMETER WITH GAIT VELOCITY. R^2 IS USED AS A MEASURE OF THE VARIABILITY IN GAIT VELOCITY EXPLAINED BY EACH SAGANGVEL PARAMETER.

	r	R^2
Mean SagAngVel mid-swing	0.48	0.23
Min SagAngVel	-0.41	0.17
Mean abs. SagAngVel	0.40	0.16
Max SagAngVel	0.30	0.09
CV SagAngVel	-0.08	0.01

MGC is sensitive to subtle changes in angular displacements of the segments of the lower extremity during the swing phase of gait [1, 13]. A study by Mills and Barrett [14] reported age-related differences in swing phase mechanics between a group of young and healthy older males. They found that while the differences in hip and knee kinematics between the young and elderly subjects were not statistically significant in isolation, their combined effect was a significantly lower rotational velocity of the shank and foot segments in the elderly compared with the young subjects at the point of heel contact. The present study has revealed similar differences in swing mechanics between fallers and non-fallers, namely a decreased overall mean absolute-valued angular velocity of the shank segment in individuals with a history of falling, along with a decreased mean angular velocity at mid-swing and decreased overall minimum angular velocity. It is currently unknown if this movement strategy is protective or maladaptive. A statistically significant reduction in shank angular velocity at the mid-swing points was observed in fallers. At the mid-swing point, the foot trajectory undergoes a precarious proximity to the ground, and so this result might suggest that fallers employ a protective strategy, adopted to moderate the risk of tripping. The plot in Figure 3 illustrating the medio-lateral shank angular velocity (gyroscope y-axis) suggests that minimum angular velocity occurs at toe-off. Decreased shank angular velocity at this point may be due to more pronounced limitations in lower limb mobility [15] and strength [16] in fallers, that are generally associated with ageing. There may be, therefore, a complex interplay between adaptive and unfavorable motor strategies during the swing phase of gait in these individuals that may require increased cognitive resources. Increased cognitive loading during gait is significantly associated with an increased risk of falling amongst older adults and frail older adults in particular [17]. Further work is required to examine these control mechanisms more closely.

It is well known that gait speed is correlated with spatio-temporal, kinematic and kinetic gait variables [14]. When examining biomechanical gait variables between groups, it is therefore necessary to account for gait speed, as this may explain the differences observed may simply be due to gait speed rather than the ageing process or clinically relevant factors. Previous research by Miller *et al.* [18] reported a reduction in MGC with increasing treadmill speed, while a recent study by Schulz [13] reported a significant increase in MGC with increasing gait speed. The inertial sensor angular velocity parameters presented here (surrogate measures of MGC) show weak relationships with the preferred gait speed recorded in this study (Table II). In addition, gait speed did not differentiate between fallers and non-fallers in this cohort.

It is interesting to note that the three parameters showing significant differences between fallers and non-fallers (mean absolute valued shank angular velocity, minimum shank angular velocity, mean shank angular velocity at mid-swing points) did not correlate strongly with two standard clinical measures of falls risk i.e. the TUG and the Berg Balance Scale. These parameters may therefore constitute a new measure of falls risk, capturing information about the faller that is not captured in other standard measures.

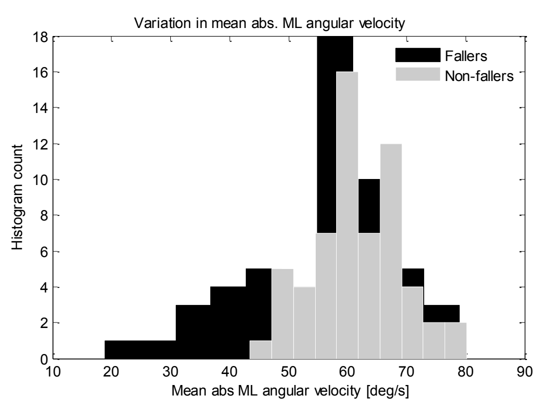

Figure 4: Histogram illustrating the distributions of mean absolute valued SagAngVel for community dwelling elderly fallers and non-fallers.

V. Conclusion

Angular velocity parameters, shown previously to relate to MGC in normal controls can discriminate between community dwelling elderly fallers and non-fallers during steady state over-ground walking. The method reported here could form part of an extra-laboratory falls risk assessment tool. Future work will seek to elucidate the control mechanisms governing differences in shank angular velocity parameters between fallers and non-fallers.

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