Quantifying Stability Using Frequency Domain Data from Wireless Inertial Measurement Units

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ABSTRACT

The quantification of gait stability can provide valuable information when evaluating subjects for age related and neuromuscular disease changes. Using tri-axial inertial measurement units (IMU) for acceleration and rotational data provide a non-linear profile for this type of movement. As subjects traverse various surfaces representing decreasing stability, the different phasing of gait data make comparisons difficult. By converting from time to frequency domain data, the phase effects can be ignored, allowing for significant correlations. In this study, 12 subjects provided gait information over various surfaces while wearing an IMU. Instabilities were determined by comparing frequency domain data over less stable surfaces to frequency domain data of neural network (NN) models representing the normal gait for any given participant. Time dependent data from 2 axes of acceleration and 2 axes of rotation were converted using a discrete Fourier transform (FFT) algorithm. The data over less stable surfaces were compared to the normal gait NN model by averaging the Pearson product moment correlation (r) values. This provided a method to quantify the decreased stability. Data showed progressively decreasing correlation coefficient values as subjects encountered progressively less stable surface environments. This methodology has allowed for the quantification of instability in gait situations for application in real-time fall prevention situations.

Keywords: Biomechanics, Biomedical Informatics, Inertial Measurement Units, Stability, Neural Networks.

1. INTRODUCTION

Using wireless inertial measurement units (IMUs) and neural network predictive software to monitor stability in aged adults or those with neuromuscular compromise presents a novel approach to fall risk reduction. These devices provide acceleration, rotation, and magnetic field parameters for characterization unlike current wearable acceleration only monitors. This paper is designed to examine the feasibility of using a NN model of an individual's normal gait for comparison to real-time frequency domain gait data over less stable surfaces to attempt quantification of instabilities. Measuring human body segments for static and dynamic balance and postural sway using three axis accelerometers in a clinical setting in the young and elderly has been shown to be reliable [1]. The quantification of motions of everyday living using accelerometers can provide useful classification data and include sitting, standing, walking, stair climbing and cycling [2]. Combining accelerometer and gyroscope data has been demonstrated by measuring knee movement during gait utilizing body mounted sensors [3]. Magnetometers have been used with gyroscopes and accelerometers to determine the posture in real time of human body segments [4]. As individuals age, there is a general degradation in balance control, either from changes in sensory perception or muscle effectiveness [5]-[6].

Research has also shown the efficacy of combining IMU data and back-propagation Neural Networks (NN) for predicting movements [7]-[9]. The complex scenario of trying to predict movements of any given individual when their normal gait data is known is shown in Fig. 1. In this case, a back-propagation neural network was trained with historical tri-axial gyroscope and accelerometer gait data from a 19 year old male. IMU Data from the subject were used in a supervised training mode with the NN. Five seconds of normal gait comprised the training set. New acceleration gait data from the same subject were presented to the network for feed-forward classification.

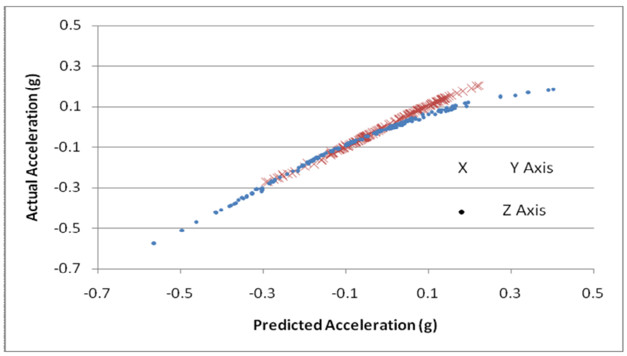

Fig. 1. Scatter plot showing actual gait data versus the NN prediction of new gait data from the same subject with Pearson product moment correlation coefficient (r) > 0.90.

There are predictable protective motions exhibited when an individual falls [10]. Research into the relationship of horizontal and vertical velocities when distinguishing normal activities from fall activities has demonstrated the potential for reducing falls [11]. This leads to the idea of establishing biomarkers that represent tracking data for when an individual is becoming unstable when involved in activities of everyday living.

Comparing "fingerprint" gait data from the same subject in good health works well when traversing similar surfaces. As stability is reduced it becomes more difficult to quantify the degree of instability since the non-linear data in time domain no longer aligns. Data involving the analysis of jaw movement has shown the efficacy of using Fast Fourier Transform for evaluating mechanical movements [12]. Abnormal gait detection utilizing Discrete Fourier Transform has been demonstrated with video motion analysis in relation to lower extremity joint angle compromise [13]. Converting to a frequency domain via Fourier analysis may eliminate the problem of correlating non time aligned data, allowing for valid correlations between a developed NN model and data derived from a subject with stability reduction. We have attempted to develop a methodology to quantify the amount of instability introduced into a gait pattern.

2. METHODS

A wireless IMU (MEMSense, L.L.C., Rapid City, SD 57702) was utilized for testing. This device has a 30 meter range (line of sight) and transmits via Bluetooth communications protocols. The IMU measures acceleration, rotation and magnetic field in 3 axes. It is a ± 5g, 600^o/s, ±1.25 gauss unit with a sampling rate of 150 Hz and measures 42.8mm x 54.2mm x 11.1mm (W x L x D). The weight is 23 grams. Power is provided by a 9 volt battery.

Normal gait was performed by 12 healthy young male and female adults (20.1 ± 1.24 years). Subjects walked for 6 meters on a hard surface, sand (approximately 75mm deep), and heavy growth vegetation (approximately 225mm deep) while wearing an IMU at the level of their center of mass (COM) or their umbilical region. In addition, 6 subjects walked on a randomly stable elevated (0.5m) platform. The relative stability on different surfaces was reported. Data recorded included x-y-z acceleration (g), x-y-z rotation (^{o}/s), magnetic field (gauss), and time (s) using the IMU. The initial and last steps were discarded to address anticipatory effects. With acceleration and magnetic field the y axis orientation aligned with lateral movements, z axis aligned with front to back movements, and the x axis aligned with up and down movements. The gyroscope recorded rotational movements about the corresponding axes shown in Fig. 2.

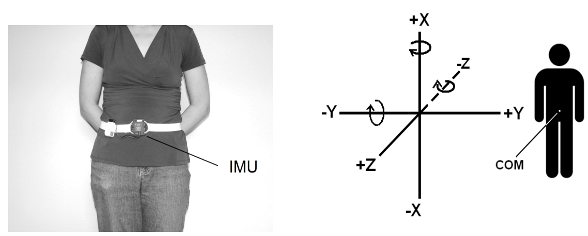

Fig. 2. Left is the orientation of IMU when worn as a belt on human subject at the COM on the right.

A back-propagation NN was used to model the 3 axis acceleration (ax, ay, az) and gyroscope (gx, gy, gz) data. A back-propagation NN was used to model the 3 axis acceleration (ax, ay, az) and gyroscope (gx, gy, gz) data. It was trained with all 6 axes of hard surface gait data. Supervised training typically required from 1000 to 2000 epochs in order to minimize the network error to < 0.005. A log-sigmoid activation function and from 0 to 12 nodes in a hidden layer were assigned. New hard surface gait values for the same subject were presented for feed-forward prediction. The goodness of fit between the actual gait data and the NN model was shown using the Pearson product moment correlation coefficient (r).

Movement data from acceleration in y and z and rotation in x and z were transformed from time domain to frequency domain utilizing Fourier analysis. The resulting frequency magnitudes seen as the subject walked on various surfaces were correlated with the NN model output frequency components. The correlation coefficients for ay, az, gx, and gz in each case were then averaged. The frequency spectrum describes the magnitude and phase of a signal or the response of asystem. The phase information is discarded to generate a frequency spectrum by examining only the magnitude or absolute value of the complex number generated by the Fourier analysis. FFTsize = 256 samples and frequency resolution fres = f/FFTsize = 150 Hz / 256 = 0.5859 Hz. The Nyquist-Shannon sampling theorem dictated 128 points for evaluation. The sample size was further limited to data below 28 Hz.

3. RESULTS

Frequency domain acceleration and rotational data in the y / z axis and x / z axis respectively showed a consistent decrease in correlation when comparing hard surface gait data from the NN model with data from the progressively less stable surfaces as shown in Table I. As the subject walks on the less stable surfaces, r values exhibit a statistically significant decrease. All participants were able to traverse the various surfaces without falling, though compromised stability was reported on the sand/vegetation and even less on the unstable platform. This indicates that small to moderate changes in stability can be predicted in gait situations.

To support the uniqueness of the frequency-domain output, NN frequency-domain models from 4 different subjects were compared. These models represent their normal gait. Average correlation coefficients between subjects were $r \leq 0.7$ (ay), $r \leq 0.3$ (az), $r \leq 0.3$ (gx), and $r \leq 0.3$ (gz), showing weak inter-model correlations.

TABLE I
Average r from ay, az, gx, gz compared to NN model.

Surface	Avg. r	S.D.	p	Reported Stability
Hard	0.9922	0.0129	0.0001	Greatest
Sand	0.7609	0.0814	0.0026	Moderate
Vegetation	0.7141	0.0777	0.0065	Moderate
Platform(6)	0.3619	0.2082	0.2270	Least

Conversion of the x and z axis rotation data to frequency domain signals is shown in Fig. 3. When comparing the NN model with the axes rotations in gait over sand, r = 0.8769 (gx) and r = 0.8409 (gz). These strong correlations suggest little but distinguishable differences in rotation over hard and sand surfaces. Increased frequency components are seen at the lower frequencies (< 7 Hz). Higher frequency components are also shown in Fig. 3. By ignoring the phase information, the problem of peak alignment in correlating various levels of stability is minimized.

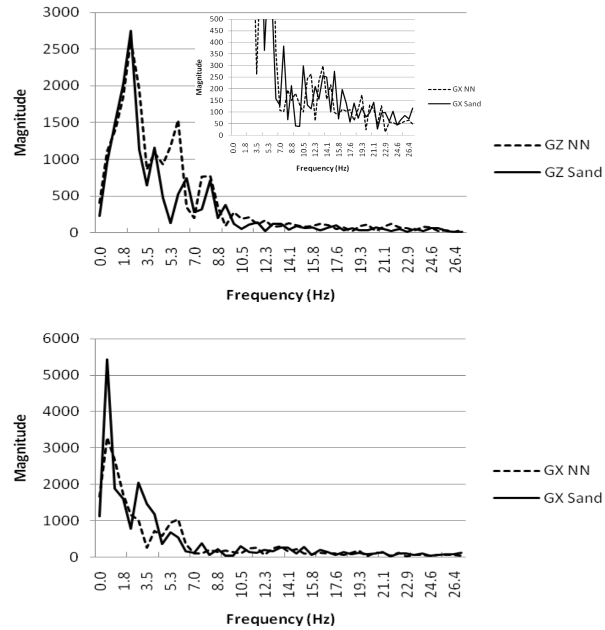

Fig. 3. Top graph shows Fourier transform data of rotation about the x axis during gait with an insert higher resolution graph, illustrating frequency components at higher frequencies. The bottom graph shows Fourier transform data of rotation about the z axis during gait.

Participants reported their perceived stability when moving over the sand, vegetation and unstable platform surfaces. 10 participants reported that the sand surface was more stable than vegetation surface. The data showed that in 8 of the 12 cases, the sand was more stable. All 6 of the unstable platform participants reported significantly less stability than either the sand or vegetation surfaces.

When the data are examined from all 12 subjects, the degraded stability can be shown when gait is on less stable surfaces. The average r values from each surface are plotted in Fig. 4.

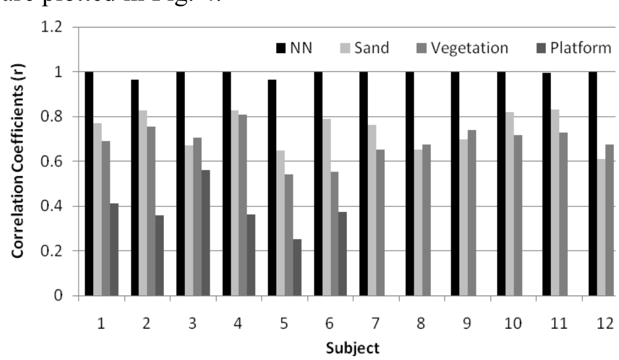

Fig. 4. For each of the 12 subjects the r value sequence is NN, sand, and vegetation (left to right). The first 6 also contain platform data (far right bar).

The frequency data shows similar correlations between sand / hard surfaces and between the vegetation / hard surfaces. The IMU acceleration and rotation values on the unstable platform are shown in Fig. 5. Notice that subject 3 showed close average r values between sand, vegetation, and the unstable platform. This individual was an athlete who exhibits superior balance control. The ay, az, gx, gz axes appear to characterize gait in such a way that meaningful quantification of stability can be attempted in gait and possibly other activities of everyday living.

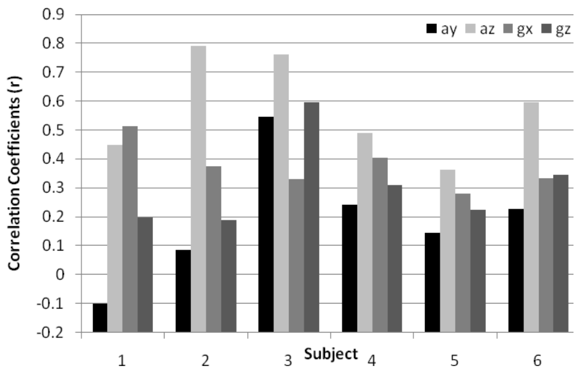

Fig. 5. For each of 6 subjects, the r value sequence over the unstable platform surface is ay, az, gx, and gz (left to right).

4. CONCLUSIONS

Using frequency domain data to compare different gait characteristics proved to be a valid method for estimating the degree of instability. Subjects reported decreased stability when walking over the sand or vegetation surfaces but not to the extent that a fall was eminent. The unstable platform was reported as the least stable surface. The corresponding correlation coefficients decreased in a predictable manner. This data indicates that wearable wireless IMU devices for real-time fall prevention in gait situations are feasible.

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