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SHIMMER: A new tool for temporal Gait analysis

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Abstract—**Development of a flexible wireless sensor platform for measurement of biomechanical and physiological variables related to functional movement would be a vital step towards effective ambulatory monitoring and early detection of risk factors in the ageing population. The small form factor, wirelessly enabled SHIMMER platform has been developed towards this end. This study is focused assessing the utility of the SHIMMER for use in ambulatory human gait analysis. Temporal gait parameters derived from a tri-axial gyroscope contained in the SHIMMER are compared against those acquired simultaneously using the CODA motion analysis system. Results from a healthy adult male subject show excellent agreement (ICC(2,k) > 0.85) in stride, swing and stance time for 10 walking trials and 4 run trials. The mean differences using the Bland and Altman method for stance, stride and swing times were 0.0087, 0.0044 and -0.0061 seconds respectively. These results suggest that the SHIMMER is a versatile cost effective tool for use in temporal gait analysis.**

I. Introduction

Detailed measurement of physical function has been possible for many years using laboratory based kinematic, kinetic, and physiological measurement equipment such as marker based motion capture systems, force-platforms, and electrophysiological sensors/electrodes. However, acquiring these measurements outside the laboratory or clinical setting has proved difficult in the past. Recent developments in wireless networking, micro-fabrication and chip integration, processing capacity as well as reduced power requirements have made the process of measuring motor behavior, posture and physiological variables over a prolonged period in a clinical or community setting a much more realistic proposition. Wearable monitoring of human function has enormous potential in health management as a means of facilitating ubiquitous measurement of physical and physiological functioning in a subject's natural environment over a prolonged period of time. It can facilitate early detection of deviations from normal function in a non clinical environment.

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For example, detection of gait asymmetry or reduced postural stability in a patient's home environment could identify the presence of degenerative diseases associated with increased risk of falling and would facilitate early intervention for falls prevention. Diagnosis could be made based on the identification of characteristics associated with gait as well as other physiological features such as heart rate and blood pressure. Measures of temporal gait parameters such as stride time and swing time, and particularly the variability of these parameters, have been shown to be useful in the prospective evaluation of fall risk in community-living older adults, and also in quantifying impaired walking performance post-stroke [1, 2]. Currently there is no systematic understanding of the optimal sensor configuration for such a wearable gait monitoring system.

The SHIMMER is a lightweight, low-power, wirelessly enabled sensor platform which can be utilized for body-worn application either using Bluetooth or 802.15.4 radio communications. The SHIMMER kinematic sensors incorporate a tri-axial accelerometer on the base board with a gyroscope daughter board which can be used to extract temporal parameters of gait [3] and represents a portable low-cost solution for in-home and ambulatory evaluation of gait. The aim of this study was to validate the SHIMMER platform as a technology for capturing temporal gait parameters in a clinical or home setting. The capacity of SHIMMER to easily and cost effectively identify key gait parameters such as heel strike and toe off was compared to that of a laboratory based marker based motion capture system (CODA, Charnwood Dynamics, UK).

II. Method

A. Experimental set-up

The gait of one normal healthy adult male (age 25) was measured simultaneously using two gait measurement technologies; the SHIMMER wireless sensor platform [3, 4] with a gyroscope daughterboard and the Cartesian Optoelectronic Dynamic Anthropometer (CODA) motion analysis system. Data was recorded whilst the subject performed multiple over ground walking and running trials along a 15m walkway in a motion analysis laboratory. In all, 10 walking trials at a self selected comfortable walking pace and 4 running trials at a self selected jogging pace were completed yielding 47 separate heel strike (HS) and toe off (TO) events for subsequent data analysis.

B. SHIMMER data acquisition

Inertial monitoring unit (IMU) kinematic data was acquired using two SHIMMER wireless sensors, one each attached to the shank of the left and right leg. Each SHIMMER contained both a tri-axial accelerometer and tri-axial gyroscope and was programmed to sample each axis at a rate of 102.4Hz (the SHIMMER platform uses a 32768Hz crystal unit (2^{15} Hz); TinyOS (http://www.tinyos.net/) firmware generates software timer events based on this hardware clock and for this study sample rates sent by SHIMMER were in 1.024 increments, hence a sample rate of 102.4 Hz as opposed to 100 Hz). Data was acquired from the SHIMMER via Bluetooth communications using a custom built application developed using the BioMOBIUS™ (http://www.biomobius.org) [5] software development environment. All post processing and analysis was carried out off-line using the MATLAB (version 7.6, MathWorks, Natick, MA, USA) programming environment. The raw SHIMMER accelerometer and gyroscope data was calibrated to derive the acceleration and angular velocity vectors with respect to the sensor unit coordinate axis. Rotation of the sensor based vectors using a sensor to segment offset orientation matrix (also referred to as a rotation matrix) produced the acceleration and angular velocity vectors with respect to the segment coordinate axis. Before further processing the raw gyroscope signal was low pass filtered with zero-phase 5^{th} order Butterworth filter with a 50Hz corner frequency.

Temporal parameters of gait were derived using the method proposed by Aminian et al [6] which applies an appropriate algorithm to determine heel-strike and toe-off events from the medio-lateral angular velocity of the shank. Fig. 1 below shows a sample of the angular velocity signal derived from the SHIMMER gyroscope from a subject walking normally. The heel strike and toe-off points for each gait cycle are marked.

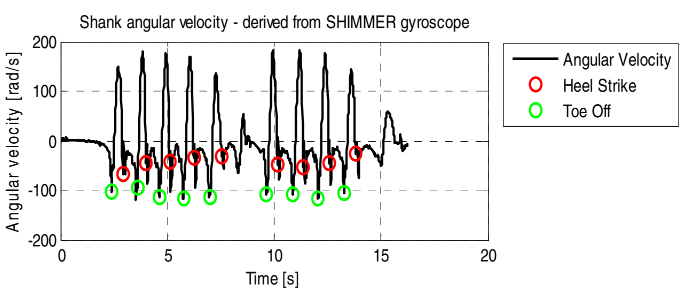

Figure 1: Sample of medio-lateral shank angular velocity signal derived from SHIMMER gyroscope during walking.

It should be noted that while it is possible to determine the medio-lateral angular velocity of the shank using a single axis gyroscope, this method requires that the gyroscope sensor is positioned such that its measuring axis is aligned with the medio-lateral axis of the shank of the leg. If a full 3-axis IMU (accelerometer and gyroscope) is used, a calibration technique similar to that outlined in [7] can be used to determine a sensor to segment offset orientation matrix. This allows for the sensor unit to be attached to the body segment at any orientation and any location while it remains possible to determine the angular velocity about each of the three standard axes of the body segment. This method requires that, with the sensor units fixed, two simple static gravity measurements are taken from each accelerometer cluster, one with the person standing vertical (to the determine the proximal-distal axis of the body with respect to the sensor unit co-ordinate axis) and a second with the person lying horizontal (to determine the anterior-posterior axis of the body). The medio-lateral axis is then determined as the cross product of the other two. The sensor to segment offset orientation matrix is then constructed using the three axes. Assuming the sensor units remain fixed, this orientation matrix will remain constant throughout the experiment and thus only needs to be acquired once. This methodology was utilized in this study.

C. CODA data acquisition

Two CODA cx1 units (Charnwood Dynamics Ltd, Leicestershire, UK) were used to acquire data, one placed at either side of the subject. The CODA cx1 unit is a commercially available optoelectronic motion capture system for recording and analyzing human movement. Two CODA infrared light-emitting diode markers were placed on the left and right foot, in accordance with the manufacturer's guidelines. Markers were positioned on the inferior lateral aspect of the heel, and the lateral aspect of the fifth metatarsal head. The CODA data was collected at a sampling rate of 200Hz. The subject performed 10 passes at a self-selected walking speed, and 4 passes at a self-selected jogging speed, yielding 47 heel strike (HS) and toe off (TO) events. The HS and TO times for each trial were calculated using algorithms reported by Hreljac et al [8]. These algorithms can predict HS and TO times with an error of 4.7ms and 5.6ms, as compared with synchronized force platform recordings, and are based on the values of the vertical and horizontal components of jerk equal to zero, respectively.

The BioMOBIUS based SHIMMER acquisition system and the CODA motion capture systems were synchronized using a dedicated CODA trigger output. This trigger is activated at the initiation and deactivated at the conclusion of a CODA capture. The trigger was connected to the analog-to-digital input of a dedicated synchronization SHIMMER. Synchronization information and kinematic data from the SHIMMER devices were simultaneously recorded within BioMOBIUS.

D. Temporal gait parameters

The heel strike and toe-off characteristic points derived using the SHIMMER and CODA systems were used to calculate the three temporal gait parameters listed below:

- Stride time
- Stance time
- Swing time

Stride time is defined as the time from initial contact (heel-strike) of one foot to initial contact of the same foot. The stance time is defined as the time between a heel-strike and toe-off point on the same foot. Similarly swing time is defined as the time between a toe-off point and the heel strike point on the same foot. In this study the data for left and right feet for each temporal gait parameter were merged. Fig. 2 provides a graphical illustration of how each temporal parameter was derived.

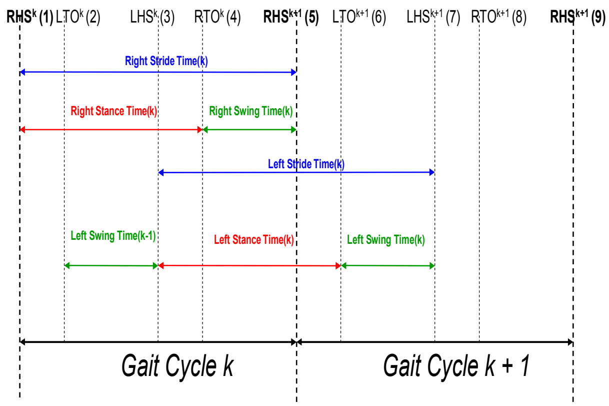

Figure 2: Calculation of temporal gait parameters using heel strike and toe-off points. RHS and LHS denote right and left heel strike respectively. Similarly, RTO and LTO refer to right and left toe-off points respectively

E. Statistical analysis

Temporal gait parameters derived from the two SHIMMERs were compared against those derived from the CODA using the mean percentage error, intraclass correlation coefficient (ICC(2, k)) [9] and the Bland-Altman method [10]. Bland Altman plots are shown to illustrate graphically the agreement between temporal parameters, simultaneously derived from SHIMMER and CODA.

III. Results

Results comparing temporal gait parameters derived from the SHIMMER to those derived from the CODA system are given in table 1.

The results show that there is excellent agreement (ICC(2, k) > 0.9) between the SHIMMER and CODA heel strike, toe off, stride time and stance time. There is a good agreement (ICC(2,k) = 0.86) between SHIMMER and CODA swing times.

Table 1:
Results for agreement between temporal gait parameters derived from both SHIMMER and CODA technologies. Mean error refers to mean percentage error difference between the SHIMMER and CODA for each temporal gait parameter.

	Mean CODA ±Std	Mean SHIMMER ± Std	Mean difference ± Std	Error [%]	ICC(2,k)
Heel Strike [s]	-	-	-0.0024±0.0343	0.6356	0.9999
Toe off [s]	-	-	0.0017±0.0560	1.3317	0.9997
Stance time [s]	1.12±0.13	1.10±0.15	0.0087±0.0181	2.5637	0.9956
Stride time [s]	0.62±0.13	0.63±0.14	0.0044±0.0116	0.9377	0.9987
Swing time [s]	0.48±0.02	0.47±0.02	-0.0061±0.0205	3.7713	0.8566

Fig.3 is a Bland–Altman plot for toe-off points calculated from data acquired using the SHIMMER gyroscope and data acquired using the CODA motion analysis system. Fig.4 is a Bland–Altman plot for gait swing time calculated from data acquired using the SHIMMER gyroscope and data acquired using the CODA motion analysis system

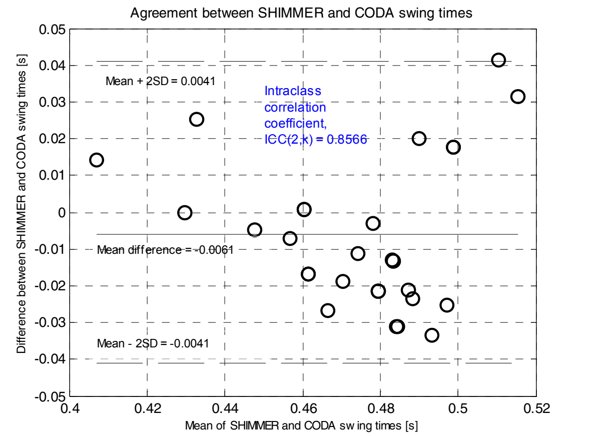

Figure 3: Bland Altman plot illustrating the agreement between the swing times derived from SHIMMER gyroscope data and those derived from the CODA motion analysis system.

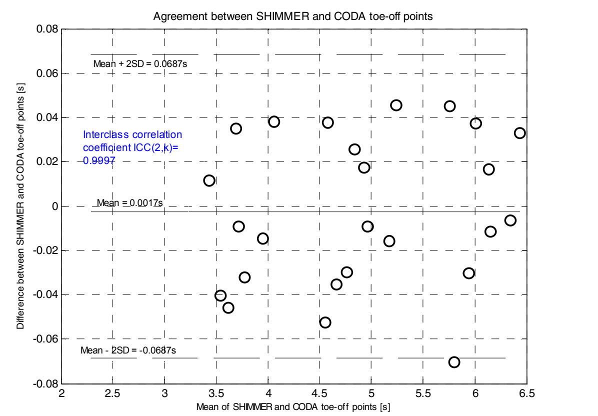

Figure 4: Bland Altman plot illustrating the agreement between toe-off points derived from SHIMMER gyroscope data and those derived from the CODA motion analysis system.

IV. Discussion

Results show that temporal gait parameters obtained from one subject using the SHIMMER wireless sensor platform compare favorably with those simultaneously obtained from the same subject using the CODA motion analysis system. Previous studies [11, 12] have validated the CODA system as a reliable platform for gait measurements so these results are very promising. The small size (50mm x 25mm x 12.5mm) and weight (>15 grams) of the SHIMMER along with its relatively low cost make it an ideal solution for in-home and ambulatory monitoring of temporal gait parameters.

Future studies will seek to validate the SHIMMER as a platform for measuring spatial as well as temporal gait parameters using a larger cohort of patients.

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