A novel approach for assessing gait using foot mounted accelerometers

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***Abstract*— Accelerometer technology is becoming increasingly smaller and cheaper to develop. As a result such devices can easily be integrated into a shoe to ubiquitously capture gait information which could potentially be used to detect development of injuries, neuro-degenerative diseases or a change in disease symptoms. Much research has been done in the past comparing accelerometer data to kinematic or spatio-temporal data; however little has been done investigating what insights into normal and dysfunctional movement patterns accelerometer data from the foot can provide. It is important to first gain an understanding of how foot accelerometer data behaves during healthy gait before developing methods to assess dysfunctional gait with such a tool. In this preliminary study we have analyzed data harnessed from tri-axial accelerometers mounted on the dorsi of the feet in 6 healthy subjects walking at different speeds (slow, normal relaxed walking, fast) to hypothesize what insights into movement and motor control accelerometer data output alone can provide. Results indicate that peak acceleration during initial swing, mean acceleration during mid-swing and peak acceleration at initial contact are main quantitative features that distinguish between walking velocities. These results suggest that quantifying specific acceleration patterns during gait may one day be useful to cheaply and easily detect gait pattern changes due to disease or injury. Though these preliminary results are promising, further work is required to investigate the utility of accelerometer use in a patient population.**

Keywords-gait; total acceleration; accelerometer; foot; swing phase; feature detection

I. INTRODUCTION

Gait analysis techniques have been used by clinicians and researchers for many years to characterize healthy gait and describe deviations during the presence of disease or injury. Measuring gait patterns provides insight into how a person's neuro-muscular system is behaving [1].

Traditionally gait has been measured using optical-electrical systems and force plates. The knowledge about gait and gait control learnt from these tools has been tremendous; however they do have three main limitations. Firstly they are expensive; to equip a laboratory with both force plates and an optical-electrical system is close to or more than half a million Euro depending on which systems are purchased. Secondly, a very high level of expertise is required to run the equipment. Often only those who have completed graduate research using these tools know how to use them. Thirdly, assessing walking gait in a laboratory setting does not necessarily reflect how a person moves in their everyday life. These three factors limit the number of patients who can be assessed with such systems and the validity of the data they collect. There is a need for cheap, ubiquitous methods of analyzing gait that will allow researchers to collect more data in a real world setting.

Another approach to analyzing gait is to use accelerometry. Accelerometers may be able to provide novel insight into movement control, especially considering that our body's vestibular and some of our somatosensory apparatus' are sensitive to acceleration [2]. Accelerometer's are small, cheap and can be manufactured into shoes to allow measurement to occur ubiquitously in every-day life [3].

The applications for this type of monitoring are plentiful, such as, early detection of neuro-muscular disease development, early signs of chronic injury development or monitoring rehabilitation progress. With a shoe embedded accelerometer gait analysis can be made available at a low cost to a large amount of people.

Much research has been done comparing accelerometer data to traditional gait analysis tools [4]. Foot mounted accelerometers have been used to determine spatio-temporal features of walking gait [5, 6]. This data is more accurate when gyroscope data is used as well [7, 8]. Kinematic measurement with inertial measurement units (IMU) is a rapidly emerging field with products available on the market that can perform these tasks, such as the Xsens MVN BIOMECH system. Much research has been done comparing multiple IMU data to outputs from optical-electrical systems. These systems are good research tools, but require the user to wear so many sensors that everyday ubiquitous use of such systems is not practical [9-11].

Previous work using accelerometers to detect abnormal gait patterns due to disease has been done utilizing sensors placed at the lumbar spine and the shoulder [12, 13]. These are promising methods; however they require a patient to place an

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extra sensor on themselves. A shoe embedded sensor would not require a patient to perform any tasks outside of what they normally do during the day.

In this preliminary study we investigate the usefulness of foot mounted accelerometer data at different walking speeds; without trying to replicate traditional gait analysis tools. An initial understanding of what foot accelerometer data looks like in healthy subjects is necessary to get an understanding of what sort of insight this data can provide and how it should be processed when going forward to analyze dysfunctional gait.

II. METHODS

Six subjects were recruited for this study; four were females and two were male. Each subject signed a consent form and ethical approval for the study was approved by the Universities ethical review board. The subjects average age was 28 years (+/- 2.83 yrs), their average weight was 61.4 kgs (+/- 13.9 kgs) and their average height was 1.68 m (+/- 0.13m).

Each subject performed 15m walking trials in a hallway. Five walking trials were taken under three different walking conditions; normal walking, fast walking and slow walking. The subjects were instructed to walk at one of the previously mentioned speeds. Speed was measured using Brower timing gates (Utah, US) over the middle 10m section of the walkway. Speed was calculated by dividing 10m by the time is took the subject to walk 10m. An Xsens MTx IMU (Enschede, Netherlands) was placed on the dorsum of each foot; attached with athletic tape. Data from the Xsens MTx sensors were analyzed using MATLAB 2009b (Natick, Massachusetts). Total acceleration was calculated from x, y and z acceleration signals by using equation 1.

$$\text{Total acceleration (TA)} = \text{sqrt}(Ax^2 + Ay^2 + Az^2) \qquad (1)$$

All three acceleration streams were transformed into TA due to the fact that looking at specific axes is very sensitive to how the sensor is mounted on the shoe. Since the goal of this research is to lead to a system that can work outside of the laboratory it was decided to use total acceleration to analyze gait. Using TA means that we can be confident that any user or machine can mount the sensor on a shoe properly and will be able to generate useful results. This is important for the case where a user is mounting a sensor on their shoe or a manufacturer is creating a shoe with a tri-axial accelerometer built in. Proper calibration is a difficult process, especially when dealing with manufacturing facilities that are outside of the country in which the product is being designed. Using total acceleration means that the accelerometer does not need to be calibrated for orientation after it has been placed in a shoe.

Figure 1 shows a typical total acceleration signal from one flat foot to the next flat foot. Total acceleration during swing generally follows a double hump pattern. The first hump is associated with acceleration after toe-off (TO) during initial swing and the second hump is associated with initial contact (IC).

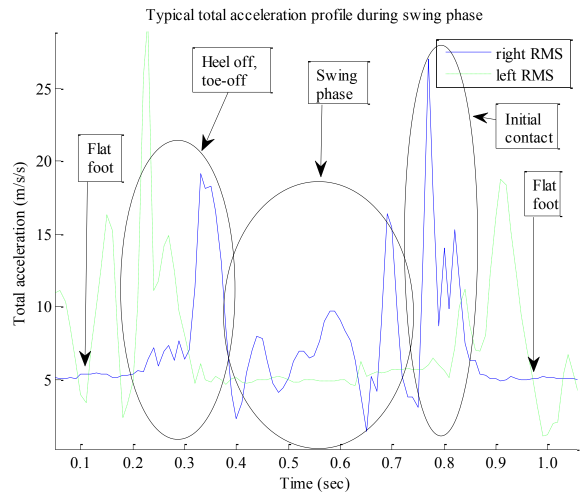

Figure 1. Total acceleration curve from an accelerometer mounted on the foot of a healthy subject.

Analysis of the TA curve indicates that there are four main phases during each stride. The first is flat foot phase, which is very quiet and the total acceleration value is not changing much, this is because the foot is on the ground and not moving during the stance phase. Secondly, heel-off and TO is at first associated with a small rise in TA and then a larger spike is seen as the foot is moved off the ground during initial swing. TO has already occurred at this spike. This spike is due to the foot beginning to move from flat foot. During the end of initial swing, TA decreases rapidly. Mid swing is associated with lower TA values and TA rises up during terminal swing. IC is associated with a sharp TA spike which is easily seen in Figure 1. This then levels out to flat foot and returns to the low value seen prior to heel-off.

TABLE I. ABBREVIATIONS FOR ACCELEROMETER VARIABLES

Accelerometer variables		Units
TASwI	Peak TA during initial swing	m/s/s
TA@IC	Total acceleration value at IC	m/s/s
TASwM	Mean TA during mid-swing	m/s/s
TTAIC	Time between peak TA initial swing to IC	sec

An algorithm was developed which calculated four variables from each foot on each stride. The peak value of TA during initial swing is useful because it shows how much acceleration the foot experiences just after TO. The second variable is the mean TA during mid-swing. The third variable calculated is the peak TA at IC. For healthy subjects this is seen as a clear sharp impact spike. There may be some relationship between this spike and IC forces as measured from a force plate. The fourth variable calculated from this data is the time between peak TA during initial swing to IC, which may be a scalar relationship to swing time. Abbreviations for the accelerometer variables are listed in Table 1.

III. RESULTS

Figure 2 shows typical total acceleration patterns during the swing phase at normal, slow and fast walking speeds. Fast walking is associated with higher TASwI values, higher peak TA@IC and smaller TTAIC times.

The average walking speed for all of the slow trials collected was 1.1 m/s, the average walking speed for the normal speed trials was 1.4 m/s and the average walking speed for the fast trials was 1.8 m/s.

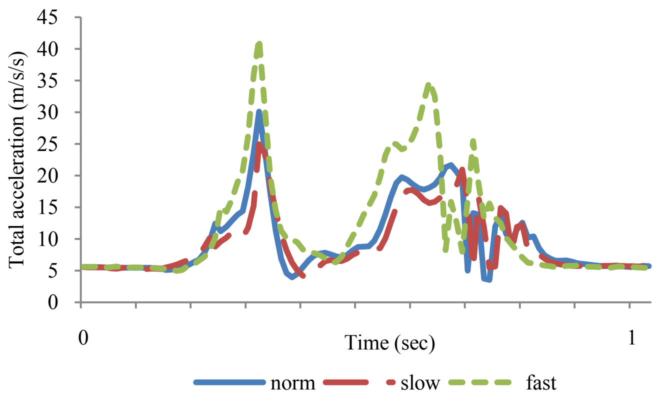

Figure 2. Total acceleration curve from an accelerometer mounted on the foot of a healthy subject walking at normal, slow and fast walking speeds.

Table 2 shows the four variables that were quantified from the total acceleration signal and how they changed due to different walking speeds. Fast walking has the highest TA values for TASwI, TASwM and TA@IC. Fast walking also has the shortest TTAIC time. Slow walking has the longest TTAIC time and the lowest TA scores.

TABLE II. GAIT VARIABLES AT DIFFERENT WALKING SPEEDS

Speed	TASwI	TASwM	TA@IC	TTAIC
	m/s/s	m/s/s	m/s/s	Sec
Normal	32.7	13.0	17.7	0.38
Fast	38.5	16.6	22.5	0.36
Slow	26.5	10.9	12.9	0.43

IV. DISCUSSION

There are clear differences in foot mounted accelerometer data between normal, fast and slow walking. In this section we analyze our results in detail to obtain a deeper understanding of what accelerometer data from the foot can tell us about the quality of a person's gait. Since accelerometers measure acceleration and the foot only accelerates around the swing phase of gait, accelerometers provide information about the foot swing characteristics of a person's gait pattern. This is the opposite of what a force-plate provides; the ground contact characteristics of a person's gait pattern.

The TA signal is flat and quiet during flat foot and first begins to increase as a subject performs heel-off. TO occurs at some point between the beginning of movement and the peak TA signal, however zeroing in exactly on TO without using a gyroscope has proven difficult to do [5, 8, 14]. This is because TO is a *soft* feature that is not associated with a sharp change in acceleration. TASwI is representative of how quickly a person begins to move their foot after TO. Healthy subjects display clear peaks that are 1.7 to 2.1 times larger than their TA@IC values.

As subjects walked faster, their TASwI increased. This was due to the fact that the foot was increasing velocity at a faster rate at the start of swing in order to complete the swing phase in a shorter period of time. TASwI may be useful in detecting disorders that result in abnormal kinematics during initial swing, such as patellofemoral pain syndrome, which causes patients to exhibit decreased peak knee flexion after TO [15].

TASwM represents how much acceleration is happening during the swing phase. A perfectly steady state velocity swing would result in TASwM being zero, since no changes in velocity would be occurring. This is not the case though, as the foot has to accelerate at the start of swing and decelerate towards the end of swing. In normal walking TA dips sharply after TASwI. This is because the foot's velocity is not changing very much as the foot is swinging. There is usually a small upside down double hump during mid-swing; in this phase perhaps qualitative analysis could be useful in assessing dysfunction. After a decrease in TA during mid-swing, TA rises up sharply again as the foot decelerates before IC.

Disorders that cause leg pain often result in the patient minimizing IC force by slowing down the swing leg before terminal swing. This dysfunctional movement pattern could potentially be detected via TASwM which would likely be increased in such a scenario due to swing leg deceleration during mid-swing. Toe-floor clearance is a cause for falls, especially in the elderly [16]. A decreased toe-floor clearance may be detectable via mean swing TA or qualitative analysis of the TA curve during swing. TASwM was the lowest while subjects walked slow and was the highest while subjects walked fast. As speed increased the subjects had a higher rate of change of velocity during swing phase. TASwM for the healthy subjects in this study was 40% of TASwI and 75-85% of TA@IC.

TA@IC represents how hard a person's foot is hitting the ground at IC. This value increased with increasing walking speed because subjects were hitting the ground harder as they walked faster. Patients with disorders that result in leg pain have altered kinematics at IC; they decrease force levels at IC to minimize pain in the damaged area [15]. TA@IC may be able to identify these changes as decreased values. This value could be used to detect early onset of an injury as well as monitor recovery from an injury, as one would want the TA@IC to return to normal as a patient went through a rehabilitation program.

TTAIC is a timing variable that decreases as a person walks faster. This time is an underestimation of the actual swing time, as the first peak in the TA signal occurs after TO. It may be fair to assume that the relationship between swing time and TTAIC is proportional. TTAIC may be useful for monitoring gait variability, which some research has suggested could be beneficial in identifying patients who are at risk of a fall [17]. For healthy gait higher TA values are associated with shorter times between the post-TO and IC peaks and faster walking speeds.

Using shoe embedded accelerometers to ubiquitously monitor gait is a large initiative with many aspects. In this study we have preliminarily attempted to describe how acceleration data itself can be used to analyze the quality of a person's gait. However, there are significant wireless communication, processing, ethical and security hurdles to overcome before such an initiative becomes a reality.

The variables described in this study come from raw tri-axial accelerometer data. They do not require computationally heavy re-orientation into a global plane. This is an important factor for usability, since such systems would be running on mobile devices with limited processing power and battery life.

V. PRACTICAL IMPLICATIONS

Preliminary analysis of foot mounted accelerometer data from healthy subjects at various walking speeds shows that clear differences in gait patterns can be picked up by outputs from the accelerometer data. These outputs could potentially provide novel insights into gait control characteristics, particularly during the swing phase. Considering the potential of shoe embedded accelerometers to decrease the cost of gait analysis and increase the number of people who can be helped, future work in this area should proceed. Future research should develop an understanding of how different diseases or injuries can be detected and monitored using the variables and methods described here.

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