Identifying Phases of Gait and Development of Walking Model from Pressure and Accelerometer Data and It's Ramifications in Elderly Walking

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Abstract. Locomotion is a feature of all animals. Whereas quadruped are fast and stable, human's bipedal gait is less stable and less efficient. Human gait analysis is going on for a long time. Such analysis usually used force data applied on the ground during different phases of gait. In this paper, we have analyzed the pressure data collected from pressure sensors placed on shoes along with accelerometer data collected from cell phones during walking activity. We identified different phases of walking activity using the pressure data. We also have developed a biomechanical model of gait based on the pressure and acceleration data.

Keywords: Gait analysis, plantar pressure sensor, gait cycle, Elderly care.

1 Introduction

Humans use their legs most frequently for locomotion. Walking is the most frequent form of locomotion for human. Studies of human locomotion have a long history [1, 2]. The reasons behind interest in the study of human locomotion have been changed over the history. Even the Greek philosophers in 500-300 B.C. studied human locomotion. Their motivation was to place harmony to nature. Recent interest in the study of gait is motivated by several factors. Doctors, for example, study human locomotion to identify the causes of problems in gait as a way find solutions. Forty-eight gait abnormalities have been identified as common occurrences by the Rancho Los Amigos Pathokinesiology and physical therapy staffs [3]. To treat these gait problems, understanding of gait is important. Prosthetic limb developer also study gait as they try to emulate human gait and other limb motions. Researchers in sports industry also study different biomedical movements of humans.

Like any other fields, study of gait needs to analyze data. Various modalities of data are used in gait analysis. For example, video data collected by multiple cameras where markers are placed in lower body locations during gait is used to analyze gait. Also, force plates are used to measure ground reaction force applied by feet during gait. One of the problems is the errors that come from measuring tools. We here propose architecture of in-shoe plantar pressure measurement system to analyze gait.

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Our major contributions:

1. We proposed a new mode of data collection system in the analysis of gait. We discussed an in shoe plantar pressure sensor system to collect data for gait analysis.
2. We analyzed the pressure sensor data collected from the shoe system and identified different stages of gait cycle. We showed how pressure data from shoes are consistent with observations from observations from other system.
3. We developed a biomechanical model for walking from the collected pressure data. We developed a similar biomechanical model for walking from data collected from phone accelerometer carried in the pocket while walking.
4. We explored the idea of applying this analysis techniques in elderly care context as a way of developing biomechanical model for elderly walking.

Section 2 discusses related works in this area. Section 3 discusses our system and gait cycle. Section 4 is discusses how pressure data collected during walking are able to identify different phases of walking. Also a biomechanical model for walking is discussed in this section. It also discusses our findings and ramifications of our findings in the analysis of elderly walking. We conclude in section 5 with a discussion of future work.

2 Related Works

Physical activity monitoring of the elderly people provides valuable information for health aware services. Most of the elderly care related research is based on video data rather than a simpler system. It is commonly observed and shown by several recording methods that freely walking people choose a certain velocity and gait pattern. At any given speed people can vary their walking pattern by changing the step length and the step frequency [7] tending to walk with optimal velocity and cadence with minimal energy expenditure [8] and [9].

Earlier, many researchers have talked about mobility and the privacy issue [5] but they didn't discuss wearing any sensors. Moreover, they do not take into account the cost effectiveness of the system. Plantar pressure distribution is related to walking speed and with increasing velocity the vertical ground reaction forces increase at heel-strike and toe-off while decreases during mid-stance [6].

It is important to be careful while interpreting observations from measurements. The ability to observe and interpret measurements of human movement has been very important factors in limiting growth of the field. Works of Ebenhart [10] and Inman [11] formed the basis for many fundamental techniques for currently used human locomotion. Currently, one of the primary techniques being used is the measurement of skeletal movement from markers placed on the skin.

3 Background

None of the existing systems for collecting data for gait analysis is perfect and suffers from different limiting factors. Either it is encumbering or expensive or requires a large fixed system. First we will discuss gait cycle during walking and then we will present the system that we used for gait data collection.

3.1 Gait Cycle

As we are concern the walking activity only, we first explain the gait cycle. There are different approaches traditionally used to address gait cycle. Each gait cycle has two phases: stance and swing. During the stance period, the foot is in contact with the ground. At the end of stance period, the toe puts pressure on the ground. So the stance period starts with a high pressure in the heel (low pressure on toe) and ends with a high pressure on the toe (low pressure on heel). During the swing period, the foot is on the air. As a result, there is no ground reaction force (GRF).

Stance again has three subdivisions. Initial double stance, single double support, and terminal double stance. The timing distribution of different phases of gait cycle is roughly as follows: Initial double stance takes 10% of time, single double stance takes 40% of time, terminal double stance takes 10% of time and swing state takes 40% of time. The duration of these gait cycle intervals varies with the walking velocity. At the normal 80m/min rate of walking, the stance and swing periods represent 62% and 38% of the gait cycle respectively. Swing also has four stages: pre-swing, initial swing, mid swing, terminal swing.

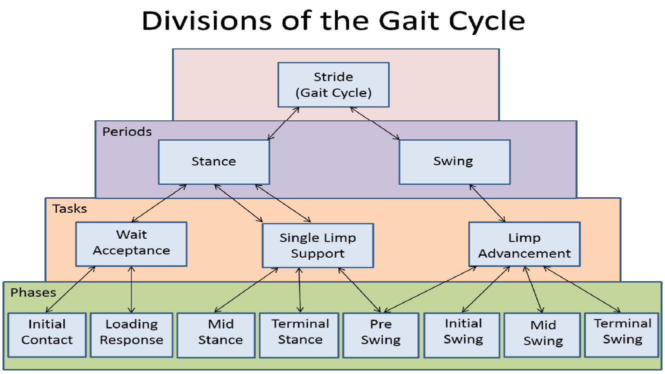

Fig. 1. Phases of Gait Cycle

3.2 Our Data Collection System

Here we used a plantar pressure system for pressure data collection from shoes developed by Lin Shu and his colleagues [4]. Eight pressure sensors are placed on each shoe. Four sensors in the front and four sensors in the back below the heel are used to collect the data. The collected data is transmitted over Bluetooth in a cell phone. We collected data for walking of a normal healthy young male subject. At the same time, we also used the phone to collect acceleration data. The phone was placed on the right pant pocket of the subject.

4 Gait Cycle from Pressure Data and Walking Model

4.1 Identification of Phases of Walking

Pressure sensor 1 and 2 are placed below heel, pressure sensor 3 and 4 captures mid foot pressure and pressure sensor 5, 6 and 7 is below the front part of the foot. Pressure sensor 8 is below the great toe capturing pressure from this part of foot. Here are the graphs from left foot while walking from pressure sensor 1 and 2 (PS1 and PS2). Pressure is measured in kilo Pascal (kpa).

Figure 2 shows how the pressure reaches peak for both PS1 and PS2 simultaneously reflecting heel strike capture by these two sensors. When the heel hits the ground, the pressure reading is highest.

So two consecutive high peak values indicates hitting of the ground by left heel twice consecutively which means a complete stride. We can see from the figure below that pressure reading from pressure sensor 8 reaches peak after pressure sensor 2. It supports the normal heel-strike-first model. We did similar graph for pressure sensor 1 and 8 and found that ps8 follows ps1 which is consistent with our expectation.

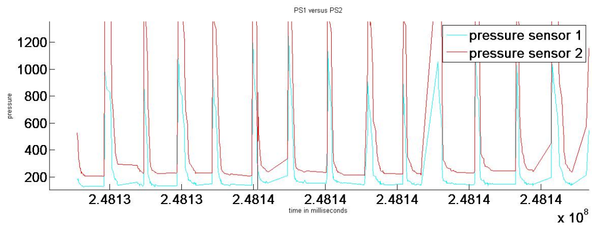

Fig. 2. Pressure in kPa at PS1 and PS2 against time

So, the very short time between red and green peak roughly reflects stance phase. According to the placement of sensors in the shoes, first ps1 and ps2 reaches peak simultaneously, then ps3 and ps4 reaches peak simultaneously, then Ps5, ps6, and ps7 reaches peak simultaneously and then ps8 reaches peak. But ps8 and ps7 should be very close and may not be differentiable.

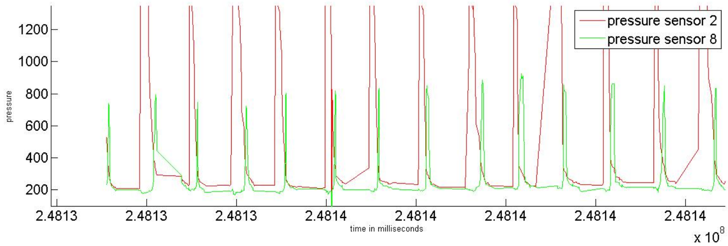

Fig. 3. Pressure in kPa at sensor 2 and sensor 8 against time

We generated similar graphs which showed that peak of ps6 and ps7 are simultaneous whereas they both reaches peak after peak of ps1. This is consistent with our observation that heel strike the ground before forefoot strike ground. All of these above figures show that stance phase is well captured by this shoe system.
From the figure below, we can see that the swing phase is also well captured. Here we are showing the graphs of left shoe against right shoe for corresponding pressure sensor. So, for example, pressure sensor 6 of left shoe is shown with pressure sensor 6 of right shoe against time. Also same pressure sensor is placed in similar place in both shoes.

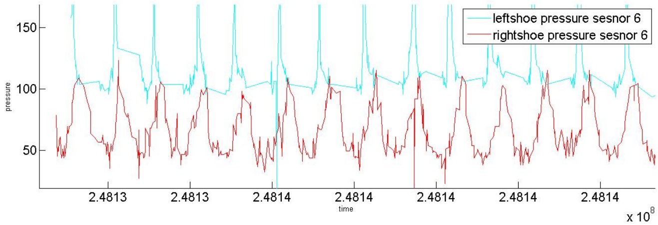

Fig. 4. Pressure in kPa at PS6 left and PS6 right against time

We can see that when the left shoe reaches peak, it is low pressure reading in the right shoe reflecting the swing phase in right shoe at that time. It is natural that the shapes of these graphs are different as the two shoe systems are not identical. Though the pressure sensors were placed in approximately similar position of both shoes, no two sensors are identical. So the different shapes are not surprising. This has been verified in case of ps6, ps7 and ps8 as we generated similar graphs for these sensors too.

4.2 Walking Model

By observing the change in pressure during walking, the first simplest approximation of the graph is a convolution of an impulse function. We will assume that the pressure curve for walking is approximated by, $p = \frac{F}{A} = \int_0^t e^{-\alpha(t-\tau)}\beta \, d\tau$ where, $0 \leq t \leq T$ and A = area = constant.

To find the impulse of the pressure, we need to integrate the signal,

$$I = \int F\,dt \quad \text{Or,} \quad I = \frac{A\beta}{\alpha}\int [e^{-\alpha(t-\tau)} + B]dt$$

$$I = \frac{A\beta}{\alpha^2}\left[e^{-\alpha(t-\tau)} + Bt\right] + C$$

Where, B, C, α, and β, are constant and B and C is unknown. We can calculate the unknown parameter by using two boundary condition and finding maxima and minima. Also assume that A is constant.

We also generated similar walking models from the accelerometer data. These accelerometer data was captured by phone carried in the pocket by the subject. The impulse, I, of a step of running and walking I s given by, $I = \int F \; dt$, where F is the force. Using Newton's second Law, $F = ma$ and $a = \frac{F}{m}$ Where, a = Acceleration and m= mass.

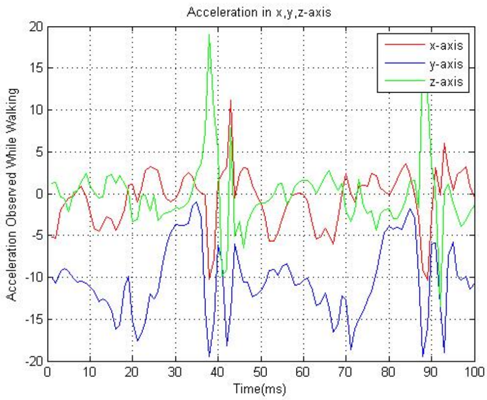

Fig. 5. Acceleration Observed with normal walking

Fig 5 is the acceleration observed for x, y, and z axis. The first simplest approximation of the graph is an impulse function. We will assume that the acceleration curve for walking is approximated by a Sinc function, $a = \frac{F}{m} = \frac{Sint}{t}$ where, $0 \leq t \leq T$

To find the impulse of the acceleration, we need to integrate the signal,

$$I = \int F \, dt \qquad \text{Or,} \qquad I = m \int \frac{Sin(t)}{t} \, dt$$

$$I = m \int \frac{1}{t} [t - \frac{t^3}{3!} + \frac{t^5}{5!} - \frac{t^7}{7!} + \cdots \ldots\ldots] dt$$

$$I = m[t - at^3 + bt^5 + ct^7 + D]$$

Where, a, b, c and D are constant and only D is unknown. We can calculate the D by using two boundary condition I(0)=0 and I(T) = 0. Also assume that m is constant.

By using the boundary condition we can express the impulse function as,

$$I = m[t - at^3 + bt^5 + ct^7]$$

5 Conclusions and Future Work

In this paper we presented how smart phone-based shoe system captures gait cycle. We showed that this system was able to capture different phases of gait cycle. We also developed a walking model from the pressure data captured during walking by the same system. Similar model was developed from accelerometer data. As a result this system can be used in the gait analysis in gait labs. In this paper, though we discussed only walking, in future, we plan to analyze and identify different phases of other activities. The system has the advantage of being portable and thus has potential to be more effective in gait analysis.

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