2013 IEEE International Conference on Green Computing and Communications and IEEE Internet of Things and IEEE Cyber, Physical and Social Computing

The possibility of normal gait analysis based on a smart phone for healthcare

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Abstract—**In this paper, through the inertial sensors or a smart phone to collect human walking gait data and then with periodic gait analysis to establish personal health counseling application. Based on regularly gait data analysis, it could find some special features of the person, such as dynamic symmetry of gait, cyclic stability of gait, and the walking patterns, also their changes with weekly or monthly. If the irregular or abnormal walking patterns like asymmetry or skew, stumbles or slip could be often detected, it may make early warning to the person that he or she may has the problem of body, possibly the falls risk.**

Keywords-inertial sensor; gait analysis; smart phone; walking pattern; healthcare

I. Introduction

In developing countries, the modern pace of life becomes very fast. People tend to ignore the physical message itself. When the disease is found, it is already very serious at the time, and thus missed the optimal treatment time or even unable to save lives. So we need to regularly or irregularly with the help of some sensors to detect slight various condition of the body. Through a comprehensive analysis by the computer, it can find some physical abnormalities and remind people to timely medical treatment. The early detection of symptoms of one disease can nip it in the bud. Currently, more and more medical institutions have adopted electronic medical records, and many health checking institutions have also put physical data into the computer. Although not full enough, but will gradually formed the electronic health records. If it is able to summarize all medical and health records of individuals, then it could be to do deep data mining, to find the information we need for healthcare and health service.

The most common activity of ordinary people is to walk. So, the walking gait could be considered to be a major determinant for a human independent motor function. Different pathologies will affect walking gait and body balance. There is a wide range of clinical disciplines involved in treatment of the disturbances of balance and the disorder of walking gait. Hence, the assessment of walking gait function can be essential in monitoring human motor function. In addition, the assessment of gait over long-term or regular periods may be useful for healthcare and predication of some diseases. The instruments and procedures of gait assessment should be not complex, inexpensive, easy-to-use, and easily available [1]. The inertial sensors and smart phone may be the suitable devices for collecting gait data. The measurement of human body accelerations is a useful technique to assess walking patterns, because subjects are not restricted to the confines of a gait analysis laboratory where most motion analysis do. Some studies have shown that it can use an accelerometer sticking on the low trunk of the tested subject to calculate and evaluate the spatiotemporal gait parameters while he or she is walking on the level ground [2]. Numerous papers have presented using inertial sensor devices or only through an accelerometer to collect gait data and do analysis [3]. Inertial measurement unit (IMU) usually contains a tri-axial accelerometer and a tri-axial gyroscope. Using IMUs will get more numbers of and more accurate spatiotemporal gait parameters than using a single accelerometer. A smart phone usually embedded with an accelerometer, a gyroscope and other sensors, they can be used for collecting gait data while the person is walking on a level ground and the phone general put on waist or thigh pocket.

II. Gait Data Collection

A. *Normal gait data collection using IMUs*

To simplify the test, we use two IMU devices (iVM-w, VMSENS, China) fixed to the left and right shank backside respectively with a Velcro strap. The original coordinates of IMU sensors need to be adjusted to the real space coordinate axes corresponding to the shanks. It needs to do some settings on the IMUs before gait testing, including sampling frequency (50~100Hz), communication port confirmation etc. The test environment usually is the general office ground corridor. When test subjects wearing the IMUs, they should stand still for 3 seconds on the start line, and then began to natural walk, and walking about 10 meters long. At the end of the walking, they also stand still for 3 seconds, and then to the next round of testing. Generally, it could be repeated three times for collecting walking data, to ensure effective gait data obtained. The purpose of the standing still for 3 seconds before and after test subjects walking, is convenient for the recognition of valid data when data processing. The raw signals from IMUs will be transmitted to a collection application on PC based on IEEE802.15.4 wireless data transmission protocol. And there through internet, the data files could be uploaded to the service platform. The gait data acquisition by IMUs is shown in Fig. 1. To put IMUs in the position of shanks rather than the choice of feet or ankles, that reason is considering the characteristics of inertial sensors. This was because the signals from the foot mounted gyroscopes were found to be more prone to noise, owing to vibration from heel impact [4].

As a comparison, we also made some experiments as putting the IMU on the waist of the human body. The purpose of the experiments is to contrast and verify the

978-0-7695-5046-6/13 $26.00 © 2013 IEEE
DOI 10.1109/GreenCom-iThings-CPSCom.2013.423

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possibility of using a smart phone for collecting gait information. All experimental results will be described in the next section.

B. Gait data collecting by sensors of a smart phone

Because the smart phones generally with a tri-axial accelerometer and a tri-axial gyroscope, so the basic principles of gait data acquisition by smart phones are the same as IMUs. But the location of the smart phone will influence the gait data processing due to the acceleration and orientation of the different parts of the body is not exactly the same when human walks. It is suggested that the tester can choose a stable location on the belt to fix the smart phone, such as the side waist, back waist, or lower waist. Another important question is to read sensor's information through the embedded software, and to record them into memory with the form of a data file, and then to upload the file to the service platform. The gait data file will be generated by the application software. And it is required to be started and stopped by the users. The current application software has not yet achieved fully automatic gait data collection and files upload. But we have tested a routine for collecting gait data 30 seconds and then stopped automatically.

Fig. 2 shows an example of personal using smart phone to collect gait data.

Fig. 1. Example of gait data acquisition by IMUs

Fig. 2. Example of gait data collection by a smart phone

Acceleration-based gait analysis is able to identify small changes in gait, showing its added value in clinical practice, e.g. diagnostics and evaluations [5]. But with the elevation of sensor technology and the decline of sensor prices, gait analysis can also be used for everyday life and ordinary people's health care. The smart phone usually combines a variety of sensors, almost everyone has one in the near future. So use a smart phone to capture someone's body information such as gait by oneself, it can guarantee a certain amount and degree of privacy [6].

III. Gait Data Processing

A. Sensor signals processing

The raw data from IMUs and from a smart phone was not exactly the same format. So the healthcare application services platform must provide many kinds of services or applications to process different styles of data files. The original coordinates of sensors need to be adjusted to the real space coordinate axes corresponding to the human body. The sampling frequency at both IMUs and the smart phone is 50Hz. The sensor signals processing works mainly include filtering for removing noise and coordinating adjustment.

It is difficult in a few seconds to solve these problems like given noise recursion, accelerometer drift, and the effect of gravity on the raw values of acceleration [7]. It is a simple solution to these issues when we use the technique of "zero velocity updating" which assesses the drift of the accelerometer with every step, and thus allows the removal of the effects of drift over one step, produces accurate displacement values after double integration [8].

To avoid amplifying noise during differentiation procedures, substantial low-pass filtering may be necessary. This may have the unwanted effect of removing components of the real signal [9]. There are many methods of signal processing, in addition to the low-pass filtering [10], it also can use Kalman filter, weighted moving average filter [11] and other methods. The raw gyroscope signals can be processed like accelerometer signals, or using different methods such as low pass filtered using Butterworth filter with a 5Hz corner frequency [12].

Fig. 3 shows an example of raw acceleration signals from a smart phone.

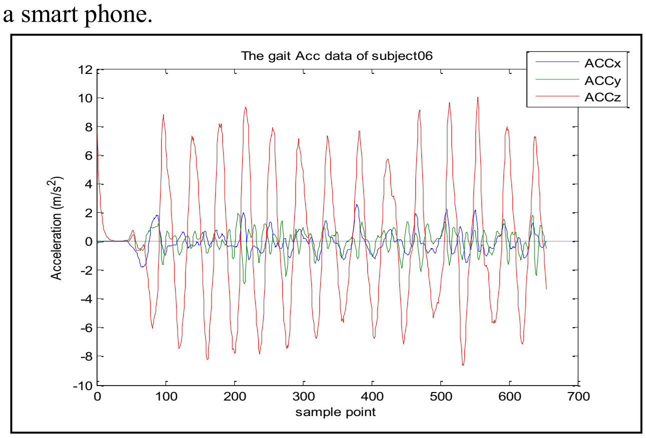

Fig. 3. The acceleration example from a smart phone test

If the signal from the sensor is relatively stable, the filtering process can be simplified. We recommend discarding the first 3 seconds and last 3 seconds instable signals, but only select the middle section of the valid walking signals to process.

B. Basic Gait Parameters Calculation

After preprocessing the gait data should be some tidy matrix vectors of acceleration and angular rate. And these vectors could be calculated to derive the angular velocity and walking speeds and other gait parameters.

With the gait data signals from sensors, the gait events could be recognized or detected. The anteroposterior acceleration signal was used to identify specific peaks corresponding to heel contact the ground (initial contact, IC). Combined with the gait vertical acceleration signals, it could be found the final contact (FC) time point of foot (or namely the toe-off, TO) [13-14]. Spatiotemporal parameters like number of steps (amount peaks), cadence (number of steps in a minute) and step duration (time of contralateral side heel contact) were determined. The walking speed may be obtained by integration of acceleration with respect to unit time (second). The walking distance could be calculated by quadratic integral acceleration on time, or the distance could be the product of the walking speed and walking time. But this way may not be so precise due to cumulative errors. To avoid integration drift, all position data were high-pass filtered (fourth-order zero-lag Butterworth filter at 0.1Hz), both the mediolateral position and vertical position. Mean step length and mean walking speed could be estimated using the upward and downward movements of the trunk [2], according to the inverted pendulum model of the body's center of mass (CoM) trajectory and using the formula (1).

$$StepLength = 2\sqrt{2lh - h^2} \quad (1)$$

Here h is equal to the change in height of the CoM, and l equals pendulum length usually the leg length. In an acquisition of walking gait data, it often contains multiple gait cycles, that is contains several consecutive steps. After step lengths were estimated for the several subsequent steps, a mean step length was calculated. The mean step length divided by mean step duration was used to estimate walking speed.

The inverted pendulum model also predicts a basic pattern of lower trunk acceleration during walking, and relationships between acceleration characteristics and spatiotemporal gait parameters. Discrimination between left and right steps was based upon an analysis of mediolateral movements of the lower trunk. According the inverted pendulum model, discrimination of left and right foot contacts can be based on mediolateral acceleration or position data. To determine which of the IC is right or left, we also can use the angular velocity around the vertical axis. They were designated by the sign of the filtered (4th order, Butterworth, 2Hz) vertical axis angular velocity at the instant of IC The positive or negative sign of the filtered signal indicates left and right ICs, respectively [15].

Then, other spatiotemporal parameters such as right or left step length (the distance between the ipsilateral and contralateral heel strikes), stride length (the distance between two consecutive heel strikes of the same foot, the average may be the twice of step length) and stride cycle time or stride duration (time of twice coherent heel contact by same foot) could be decided. And some indices of gait also could be calculated for example the step time asymmetry was to indicate differences between left and right leg movements [16-17].

Table I is an example of some average gait parameters from normal people.

TABLE I. PARTS OF STANDARD FOOTPRINT FEATURES

Age (y)	Stride Length (m)	Right Step Length (m)	Left Step Length (m)	Stride duration (s)	Speed (m/s)
20+	1.36	0.67	0.69	1.14	1.19
30+	1.34	0.68	0.66	1.12	1.20
40+	1.28	0.65	0.64	1.07	1.19
50+	1.31	0.66	0.66	1.10	1.19
60+	1.25	0.63	0.62	1.14	1.10

In order to facilitate the long-term monitoring of gait changes, select basic gait parameters as shown in Table II for statistical analysis in the future.

TABLE II. THE BASIC GAIT PARAMETERS

Parameters	Definition
Gait cycle time (s)	the time between two consecutive heel strikes of the same foot, same as stride duration
Stride length (m)	the distance between two consecutive heel strikes of the same foot, usually the first foot
Right step duration (s)	the time between right heel strike to left heel strike
Left step duration (s)	the time between left heel strike to right heel strike
Right Step length (m)	the distance between right heel strike to left heel strike
Left Step Length (m)	the distance between left heel strike to right heel strike
Right Swing phase (s)	the duration from right toe-off to right heel strike
Left Swing phase (s)	the duration from left toe-off to left heel strike
Right support phase (s)	the duration from right heel strike to right toe-off
Left support phase (s)	the duration from left heel strike to left toe-off
Double Support time	the sum time of the duration from right heel strike to left toe-off and the duration from left heel strike to right toe-off
Walking Speed (m/s)	the average instantaneous speed within the gait cycle
Cadence (steps/min)	the number of steps in a minute

All the right and left parameters may not be so easily calculated when the tester is using a smart phone. In our experiments, the position of the smart phone is back waist of human body. In this case, the effective parameters are Gait cycle time (s), right and left step duration (s), right and left swing phase (s), double support time (s), and Walking Speed (m/s). Other parameters also can be calculated, but we did not suggest doing so because the cumulative errors may a little large than we thought.

IV. Gait Analysis and Evaluation

A. Inertial Sensor Based Human Gait Attributes

To be defined inertial sensor based human gait attributes, including dynamic properties, periodic properties, average properties and bilateral attributes.

The dynamic properties are {Cycle Time, Right/Left Step duration, Right/Left Swing phase, Right/Left Support phase, Double Support time}.

The periodic properties are {RIC, LTO, LIC, RTO}. Here R refers to right foot and L refers to left foot, IC is initial contact and TO is toe-off, also sometime use FC (refer to final contact).

A complete gait cycle is defined as beginning from RIC to the period until the next RIC. Examine multiple consecutive cycles can be found: RIC-LTO and LIC-RTO periods were the double feet support phase; while LTO-LIC and RTO-RIC periods were the left and right foot swing phase respectively. Because normal human walking is an alternating left and right foot forward course, so in continuous walking cycles the order of RIC-LTO-LIC-RTO-RIC-LTO-LIC-RTO-RIC is fixed. Thus, it can be easily calculated the parameters for each gait cycle.

The average properties are walking speed, mean step length, step rate (cadence), mean stride length, mean cycle time, and so on.

The bilateral attributes are {RSD, LSD, RSP, LSP, RPP, LPP}. Here R refers to right foot and L refers to left foot; the SD is step duration, SP refers to swing phase and PP refers to support phase.

For example, RSD is the time period of RIC-LTO-LIC, and LSD is the time period of LIC-RTO-RIC.

RSP is the time period of RTO-RIC, and LSP is the time period of LTO-LIC.

RPP is the time period of RIC-LTO-LIC-RTO, is the right foot unilateral stance time. LPP is the time period of LIC-RTO-RIC-LTO.

Besides the mean value, the other three set of properties should be dynamic or cyclical changed. The values of these properties can be used to calculate the dynamic indicators.

B. Normal Walking Gait Evaluation Indicators

It must create a gait evaluation system suitable for ordinary people. The contents of the gait evaluation index system identified as follows: the gait stability indices, the gait symmetry indices, the abnormal level index and the disease-related indices. These indicators are not only for normal gait of ordinary people but also of course can be applied to abnormal gait caused by some diseases.

The gait stability indicators can be divided into the natural gait cycle stability, fast gait cycle stability, slow gait cycle stability, and so on. The gait symmetry indicators can also be similarly subdivided into more specific targets. The abnormal gait level also contains several small indicators relating to composition. The disease indices may be related to some special diseases, so not discuss here and leave to the future research.

The detail gait evaluation index system could be constituted by follow equations.

Walking stability mainly reflected in the behavior of the regularity and the stability of the cycle. It is defined by the similarity of gait properties in continuous cycles. Also it can be expressed as the difference of the same property in the longitudinal cycles.

$$STAB_{dyn}(P_J) = \sum_{i=1}^{n-1} \left| P_J(i+1) - P_J(i) \right| \tag{2}$$

Here P_J is one of the dynamic properties and the set elements be simplified by acronyms to {CT, RSD, LSD, RSP, LSP, RPP, LPP, DSP}. The subscript $i+1$ and i indicate the cycle numbers, there may be n cycles in a test.

The gait cyclic stability also can be described by the variability of the cycle stability features [18].

$$STAB_{cyc} = \frac{1}{8} \sum_{i=1}^{8} \delta(P_J) / \mu(P_J) \tag{3}$$

Here we use $\delta(P_J)$ as the standard variance of properties P_J and $\mu(P_J)$ indicated the mathematical expectation of properties P_J. Also P_J is one of the dynamic properties.

The dynamic symmetry is defined by the difference between right and left properties in every cycle. But normally, it can be simply calculated using the standard variance and mathematical expectation values.

$$SYMM_{nor} = \sum_{i=1}^{3} \left| \delta(LA_i)/\mu(LA_i) - \delta(RA_i)/\mu(RA_i) \right| \tag{4}$$

Here LA_i is one element of the set {LSD, LSP, LPP}, and RA_i is one element of the set {RSD, RSP, RPP}. The $\delta(A_i)$ is the standard variance of properties A_i and $\mu(A_i)$ is the mathematical expectation of properties A_i.

The dynamic symmetry indices may be the differential summary by comparing the values of the same attribute of right and left foot on every cycle.

$$SYMM_{SD} = \sum_{i=1}^{n} \left| RSD_i / LSD_i - 1 \right| \tag{5}$$

$$SYMM_{SP} = \sum_{i=1}^{n} \left| RSP_i / LSP_i - 1 \right| \tag{6}$$

$$SYMM_{PP} = \sum_{i=1}^{n} \left| RPP_i / LPP_i - 1 \right| \tag{7}$$

Equations (5) to (7) are all close to the value zero. Any value is big larger than zero, that is not a good symptom.

Abnormal level is defined as a function of several factors.

$$A\_L = \sum_{j=1}^{8} STAB_{dyn}(P_j) + STAB_{cyc} + \sum_{k=1}^{4} SYMM_k \tag{8}$$

Here, subscript j indicates the elements of set {CT, RSD, LSD, RSP, LSP, RPP, LPP, DSP} and subscript k indicates the elements of the collection {nor, SD, SP, PP}.

The value of A_L equation is indicative meaning only. In general, the greater the value, the body situation is not so good enough.

V. Healthcare Application Services Platform

Although there is some software of gait analysis and gait evaluation on PCs, but in order to promote the use of data mining applications, it will establish a long-term gait monitoring and gait analysis application service platform for individuals and ordinary users. Through this service platform system, it may allow the users to early detection of subtle changes of body organs, help them to know their own health status in time, and make the general public to appreciate experience the charm of advanced science and technology.

When people do not feel ill or just have slight discomfort, they usually do not go to the hospital for medical examination. Some early symptoms of the disease are unable to be found. Any discomfort in the body will reflect on his or her behavior which is walking posture or gait. So gait analysis on a regular, that is daily, weekly, or monthly, it could find some subtle changes of the body. If someone wants to explore the depth reasons of the subtle changes of gait or gait disorder, it could remind people to go to professional medical institutions and do a thorough physical examination or to see a doctor and do detailed medical check for finding early symptoms of some disease as soon as possible.

The main purpose of building a healthcare application service platform is not to diagnose diseases, but is to improve the healthcare consciousness of ordinary people. The platform may collect or receive a person's gait data every week or a certain period of time. Then the application will carries on a series of processing and comprehensive analysis. At last, the application services platform may give out a health status evaluation to the person. According to individual actual situation of body, the person may get some special warnings, such as medical check advice. Users can be connected to the platform in a variety of ways, such as the use of mobile phone or mobile devices, or directly through a computer on the internet to request their own gait analysis report. If there are long-term gait data could be analyzed, then the system could also display a trend chart, etc. The gait analysis report could be customized on user's demand, on a regular duration (e.g. weekly) from the system pushed down into the user's personal e-mail box or the smart phone application.

VI. Conclusion and Future Work

Instrumented gait analysis has become a valid tool for clinicians in the last decade, even though some factors limit its potential application. But these factors may disappear with the developing of pervasive using of microprocessors and smart devices. With further development and more validations, the smart phone sensor-based system may eventually become a useful tool for continually monitoring spatiotemporal gait parameters in a natural environment. There are many applications could be developed. Objective assessment of balance and mobility in elderly populations using body-worn sensors has recently become a prevalent theme in falls-related research. There is evidence that even pathologies at subclinical phase may be detectable by a standard gait analysis test [19]. For some early stage of diseases may not primarily affect plain gait at self-selected speed, it is more challenging research to the human locomotion and specific gait styles of many subclinical cases.

Although there are a lot of professional medical equipment and devices can monitoring the situation of human body, but most of them are expensive and inconvenient, only limited clinical or laboratory use. In addition, with the upgrading of electronic hardware devices, smartphones performance is getting better and better, and the price is getting cheaper. Using the smartphone sensors to measure human body's movement, is a non-intrusive way that does not cause any harm to human body and does not affect daily life of the users. Through our experiments, we believe that the use of smart phones to do normal gait analysis is feasible and also possible. In the near future, there will be many similar applications appeared.

We will improve the processing procedure and simplify the processing method, then make the smart phone to directly process the sensor signals, even do some gait analysis. If your smartphone is able to accurately distinguish different actions in your daily life [20-22], then it may be fully automated to do gait acquisition and analysis.

Another aim of our researches is to find some subtle variations of gait by long-term analysis of the particular person, such as the early symptom of some illness of human body, then to take some rehabilitation treatment in order to avoid some diseases for the elderly.

Acknowledgment

This work was sponsored by Shanghai Leading Academic Discipline Project, Project Number: J50103. We would like to thank all of our volunteers participating in the data collection and supporters.

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