Development of Wearable Sensor Combinations for Human Lower Extremity Motion Analysis

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Abstract – A wearable sensory system for human lower extremity motion analysis is proposed, and an intelligent computation method for this sensory system is presented. The standard method for human motion analysis is the optical motion analysis using high-speed cameras to record human 3D motion, but this method is only limited in the laboratory research, because it requires expensive devices, large space and time-exhausted calibration experiments. In this study, two low-cost human motion analysis systems are constructed, deferent from the conventional 3D motion analysis system based on high-speed camera. These wearable systems incorporate gyroscopes (ENC-05EB) to measure angular velocities of body segments, and two-axis accelerometers (ADXL202) are used to measure the accelerations for the purpose of leg (foot, shank and thigh) motion analysis in every human motion cycle. The first wearable sensor system is designed for only foot motion analysis and the second system can be used for a leg (foot, shank and thigh) motion analysis. Then Based on the two sensor systems, a fuzzy inference system (FIS) is developed for the calculation of the gait phases fed by sensors outputs. A digital filter is also designed to eliminate noises from of the output of the fuzzy inference system, which enhances robustness of the system. Finally, experimental study is conducted to validate the wearable sensor systems using an optical motion analysis system (Hi-DCam).

Index Terms - human motion analysis; motion sensor; gait phases; Lower extremity; fuzzy inference.

I. INTRODUCTION

Human motion analysis have been becoming important, for example, the dynamics analysis of pregnant woman walking can illustrate the different body dynamic conditions that ankle joint moment and hip joint moment are much larger than non-pregnant women. Based on this analysis result, the assistant and rehabilitative devices can be developed for pregnant woman or patients [1]. Now the standard method for human motion analysis is the optical motion analysis using high-speed camera to record human motion. The integration of three-dimension motion measurement using multi-camera system and reaction force measurement using force plates has been successfully devoted to tracking human body parts and performing dynamics analysis of their physical behaviors in a complex environment [2][3].

However the optical motion analysis method needs sizeable work space and high-speed graphic signal processing devices, and as we all know, for this analysis method, the devices are expensive, and the initial calibration experiments and offline analysis of recorded pictures are very complex and time-exhausted. Therefore, this method is only limited in laboratory research, and can’t be used for daily applications. Moreover, human body is composed of many highly flexible segments, and the up-body motion of human is especially complicated for accuracy calculations. Thus, in the development of cheaper and more comfortable gait analysis device, several sensor combinations, including force sensitive resistors, inclinometer, goniometers, gyroscopes and accelerometers, were proposed to perform gait phases analysis. In the study by S. K. Ng and H. J. Chizeck [4], measurements from goniometers at the hip, knee and ankle joints were used in combination with a fuzzy model classification method to detect five different gait phases. However, the method suffered from frequency detection errors, and the measurement devices also make human feel uncomfortable. In [5], K. Tong and H. M. Grant proposed a measurement device using two gyroscopes, one placed on the thigh and the other one on the shank, which can estimate knee rotation angle during walking. This system can detect different phases of human walking, but the quantitative analysis for leg motion was finished in this study. In [6], R. Willemsen et al. proposed a detection system using accelerometers, but this system just can separate stance phase and swing phase from the human walking gait phases. Ion P.I. Pappas al. in [7] used a detection system consisting of three force-sensitive resistors that measure the force loads on a shoe insole and a miniature gyroscope chip that measures the rotational velocity of the foot. The system detects accurately and reliably the four gait phases in real time, but it was just designed for the application of functional electrical stimulation.

In this paper, we respectively introduce two motion analysis systems for the foot motion analysis and the leg segments’ motion analysis during human’s walking. The first motion analysis system is the combination of two gyroscope-chips that measure two-direction rotational velocities of the foot and a two-axis accelerometer-chip that can output two-direction accelerations of the foot during walking. Based on this sensor system, a fuzzy inference system (FIS) is developed for the analysis of sensors’ outputs, which can estimate a gait phase analysis result. To get the clear gait phases change
points of human walking, a digital filter is used to remove noises from the outputs of the fuzzy inference system. Finally, experimental study is conducted to validate the motion results of the wearable sensor system by using the conventional optical motion analysis system. By using the same method, we also develop a second wearable sensor system for the whole leg (foot, shank and thigh) motion analysis.

II. FIRST SYSTEM FOR FOOT MOTION ANALYSIS

A. Methods and Material

The motion analysis system performs the detection of gait phases by using two types of inertial sensors, i.e., two gyroscopes used to measure angular velocities of two-axis on the foot plane during walking, and a two-axis accelerometer used to measure total transmission accelerations including gravity acceleration and dynamic acceleration along two sensitive axis.

In this paper, a normal walking gait cycle is divided into four different gait phases, i.e., stance, toe-rotation, swing, and heel-rotation. The definition of the gait phases is given as followings (as shown in Fig. 1). The stance phase is defined as the period when the foot contacts with the ground with its entire length. The toe-rotation phase is defined as the period following the stance phase during which the front part of the foot is in contact with the ground and its heel rotates around toe joint. The swing phase is defined as the period when the foot is lifted apart from the ground in the air. Finally, the heel-rotation phase is defined as the period after the swing phase which begins with the first contact of the foot with the ground (usually the heel, but not necessarily), then the front part of foot rotates around heel’s contacting point, and ends when the entire foot touches the ground.

We define the walking cycle (walking cycle number \( k = 1, 2, \ldots \)) as the period from one stance phase of the foot to the next stance phase of the same foot. In every walking cycle, the time points of gait phases transition from stance phase to toe-rotation phase, toe-rotation phase to swing phase, swing phase to heel-rotation phase and heel-rotation phase to stance phase are defined as \( T_{41}(k), T_{42}(k), T_{43}(k) \) and \( T_{44}(k) \) respectively. The loop frequency of the phase record is 100 Hz, i.e., equal to the sensors sampling frequency, and the sampling time points is defined as a integer value \( i \) (i = 1, 2, 3,\ldots). The foot angular displacement \( \theta(i) \) can be calculated using (1) and (2), because the angular velocity of the foot \( (\omega(i)) \) can be measured using the wearable sensor system. However the gyroscope in the sensor system is a kind of inertial sensor with static float error, so the integral calculation in (1) should produce cumulated errors in the whole walking motion analysis.

\[
\theta(i) = \theta(i-1) + (\omega(i-1) + \omega(i))\Delta t / 2 \quad (1)
\]

where

\[
\theta(0) = \theta_0; \quad i = 1, 2, 3,\ldots \quad (2)
\]

Based on the gait phase analysis of human walking, the human motion analysis can be implemented by calculating body segments’ angular displacements using inertial sensors. In (3) and (4), \( \theta(j)(k) \) and \( \omega(j)(k) \) are respectively defined as the angular displacement and angular velocity of the body segment in \( k \)th walking cycle, and the integral calculations are made in every walking cycle, which can decrease the cumulated errors in the longtime walking experiments.

\[
\theta(j)(k) = \theta(j-1)(k) + (\omega(j-1)(k) + \omega(j)(k))\Delta t / 2 \quad (3)
\]

\[
T_{41}(k) \leq j < T_{43}(k) \quad k = 1, 2,\ldots \quad (4)
\]

An electrical base board is designed for the inertial sensor system. Two miniature gyroscopes (Murata ENC-03J, size 15.5×8.0×4.3 mm, weight 10 g) are integrated on the baseboard with their sensing axis oriented on the bottom plane of the foot respectively. The two gyroscopes can measure two-dimension rotations of the foot in that plane. The Murata ENC-03J gyroscope measures the rotational velocity by sensing the mechanical deformation caused by the Coriolis force on an internal vibrating prism. The gyroscope signal is filtered by a third-order band-pass filter (0.25–25 Hz) with a 20-dB gain in the pass band. The signals with the frequencies outside the pass-band are filtered out because they are not related to the walking kinetics. The filtered gyroscope signal is used to directly estimate the angular velocity of the foot and it is integrated to estimate the inclination of the foot relative to the ground. The accelerometer-chip (ADXL202) with almost the same theory as gyroscope-chip is fixed on the back of the base board, which can measure two-axis accelerations including gravity acceleration and dynamic acceleration during walking. In the design of data record device, the sampling time of A/D module is selected according to the bandwidth of signals, and the sampling frequency should be higher than 2×1.25×25 Hz (the bandwidth of the inertial sensors’ signals is about 25 Hz) [8]. Therefore the sensor signals are sampled at a frequency of 100 Hz=62.5 Hz with a resolution of 14 bits through A/D card (Keyence NR-110), and the sampled data are saved into the person computer for the analysis. The card is connected with computer through micro-card interface of PCMCIA2.1 in personal computer. Since the two kinds of inertial sensors are low-energy consumed electrical devices, the motion analysis system is powered by using two button batteries (CR2032), which can last 30 minutes in walking experiments.

A mechanical shoe (see Fig. 2) is designed to fix the base board of inertial sensors. The foot plane is parallel to the baseboard. The material is selected as Aluminum, and the weight is about 500 g, the size is almost the same as common shoes.
B. Rules designed for Gait Phases Detection

Physics sense analysis of every phase is performed to prepare design rules for the gait phase detection algorithm. As shown in Fig. 3, when the motion measurement device is worn under the foot, it is supposed that the subject is viewed from the lateral side and clockwise rotations are considered positive. The Z-axis is vertical to the foot plane, and X-axis and Y-axis are along length- and wide- orientations of foot respectively. The symbols $\omega_x$ and $\omega_y$ represent the rotational velocity of foot around X-axis and Y-axis respectively. Physics senses of each phase can be defined as following:

1). If $\omega_x=0$ AND $\omega_y=0$ AND $A_x=0$ AND $A_y=0$ Then ‘Stance Phase’;
2). If $\omega_y<0$ AND $A_x\neq0$ AND $A_y\neq0$ Then ‘Swing Phase’;
3). If $\omega_y>0$ AND $A_x\neq0$ AND $A_y\neq0$ Then If the case is before the ‘Swing Phase’ of the same walking cycle Then ‘Toe-rotation Phase’ Else ‘Heel-rotation Phase’

C. Experimental Study on Gait Phases Detection by Using the Sensory System

When the experiments data are recorded in the hard-disk of personal computer, the off-line analysis is made to analyze the gait during walking (Fig. 4). The inertial sensors output signals are easy to be disturbed by external noises of testing environment, and the static float of the inertial sensors can also decrease the precision of the measurements in the case of long time testing. Therefore, a fuzzy inference system (FIS) is proposed to improve precision of the detection of gait phase. The fuzzy system is robust to the noise from the inertial sensors. We design the fuzzy inference system by the aid of MATLAB software. The two gyroscopes’ outputs and the accelerometer’s two-axis outputs are defined as the four inputs of the FIS, and the output of FIS is a value of gait phases.

In the design of fuzzy inference system, Mamdani fuzzy inference method is used in the inference engine. Every fuzzy input has three fuzzy sets: negative, zero and positive, and every fuzzy set is defined as saw-tooth function. In the same way, the output of FIS is defined as four fuzzy sets to de-fuzzy inference results in the Mamdani method. As shown in Fig. 5, the four output ranges is named as: stand, toe-r, swing, and heel-r respectively, and the human walking can be separated into four phases.

D. Design of a Digital Filter

In this section, a digital filter designed for the outputs of FIS is presented. The inertial sensors are sensitive to the environmental noise, which leads to the difficulty of detecting the gait phases precisely using a simple algorithm in a micro-computer. To get the decided gait phases change points of human walking, a digital filter is used to remove noise results from the fuzzy inference system. We recorded the inertial sensor system’s signals at a frequency of 100Hz, and the normal human walking period is about 1.5 sec, so in the results of FIS the pulse interrupts with period of no over 0.05 sec can be confirmed as the errors pulses in the gait phase detection. A digital filter was designed to filter the error pulses in the results of FIS. The symbols R(i) and Rf(i) represent the output result of FIS and last filtered results on the i-th sampling cycle (i=2,3,4…), and k represents the noise pulse swing value. Then the rule of the filter is designed as follows. If the absolute value of $R(i-1)$ subtracted by $R(i+3)$ is far no more
than k, and one of the absolute value among \( R(i) \) subtracted by \( R(i-1) \), \( R(i+1) \) subtracted by \( R(i-1) \) and \( R(i+2) \) subtracted by \( R(i-1) \) is larger than k, then the value of \( R(i), R(i+1) \) and \( R(i+2) \) is set as the same value as \( R(i-1) \), because in this case the 50ms sampling range (from \( i-1 \) to \( i+3 \)) must be added in a noise pulse (see Fig. 6).

Fig. 4 Four recorded signals of the inertial sensors

Fig. 5 Gait phase analysis result of a subject

Fig. 6 Theory of the digital filter

E. Experimental Validation by Comparing the Estimation Results of the Wearable System with an Optical Motion Analysis System’s

To validate the wearable motion analysis system’s performance we have compared the results from the wearable system with the measurements obtained from the commercial optical motion analysis system Hi-DCam (NAC image technology, Japan). Hi-DCam tracks and measures the three-dimensional (3-D) trajectories of retro-reflective markers placed on the subject’s body. In this experiment, the four retro-reflective markers have been placed on the toe, heel ankle and knee. Two Hi-DCam cameras with sampling frequency 100 Hz are used to track the marker positions with accuracy of ±1 mm. The markers’ trajectories from the outputs of Hi-DCam are used to validate the accuracy of the foot motion analysis system’s estimation results. We synchronized the measurements of the two motion analysis systems, and Hi-DCam can directly calculate the subject’s foot angular displacement as the references. In the wearable motion analysis system, the foot angular displacement can be estimated using (3) and (4), and the results in the estimation of foot angular displacement are plotted in Fig. 7 as comparison with that from the optical motion analysis system.

III. SECOND SYSTEM FOR LEG-SEGMENTS MOTION ANALYSIS

Based on the first wearable sensor system and its experimental results, the second wearable sensor system for the whole leg (foot, shank and thigh) motion analysis is developed. This second system can be used for synchronous analyses of foot motion, shank motion and thigh motion, in which a new inertial sensor combination and special data-recorder are designed.
The eight-channel data-recorder is special designed for the second wearable sensor system. A micro-computer PIC (16F877A) is used in the design of the pocketed data recorder, and sampling data from sensors can be saved in a chip of SRAM which can keep recording for five minutes. The off-line motion analysis can be performed by feeding the data from the SRAM through RS232 communication to personal computer. The sensor modules including a gyroscope and accelerometer combination module and two gyroscope modules are made using the same method as the first sensor system, which integrate the sensor chips and conditional circuits to measure the leg segments’ motion. Since gyroscope (ENC-03J), accelerometer-chip (ADXL202) and PIC system are device with lower working current, the second wearable sensor system is powered by using a small battery of 170 mAh (NiMH 17R8H).

C. Experimental Study

A testing experiment is implemented on the second sensory system on measurement of leg motion during normal walking. We use the same method introduced in the first sensory system’s study. In every stance phase of walking cycle, the calibration is implemented to let initial integral constant be zero.

The experiment of the second sensory system for leg motion analysis is finished through the following three steps. Firstly, the sensor devices are worn on the subject’s leg to measure 2D motion of the foot, shank and thigh, and the sensors’ data are saved in the pocketed data recorder. Secondly when the human motion record is finished, the data in the data recorder will be fed into personal computer through serial port RS232, then leg-motion data is prepared for the offline motion analysis computing. Finally, by using the same analysis method as the first foot-motion sensor system, the leg motion analysis can be performed to estimate the leg segments’ angular displacements.

Fig. 10 shows the gait phase analysis results of a subject, which can give the gait phase transition points information of this subject during normal walking. Based on the results of the gait phase analysis, in every transition point of swing phase and heel rotation phase, the calibration is implemented to let initial integral constant be real angle of the shank and thigh segments. The two-axis accelerometer is used to measure the angle in this calibration point. The foot angular displacement can be calculated using the same calibration method as the first foot motion analysis system.

The foot, shank and thigh angular displacements (θ₁, θ₂ and θ₃) can be estimated using (3) and (4), because the angular velocities (ω₁, ω₂ and ω₃) of the three segments can be directly measured by the attached gyroscopes, and the cycle initial calibration angle of each segment can be decided according gait phase analysis results. As shown in Fig. 11, the object’s leg segments’ rotational angles are obtained for the walking analysis experiment using the wearable sensor system.
IV. CONCLUSION

For human low extremity motion analysis, we have developed two wearable sensor combination systems. About the first sensor system, a different motion analysis sensor combination that reliably identified the gait phase transitions between stance, toe-rotation, swing, and heel-rotation, is presented. Validation experimental study is proposed for this new sensor system to validate the motion analysis results. We almost got the same results in the estimation of foot rotational angle displacement in the two motion systems of an optical motion analysis system and the wearable sensor system. This wearable analysis system is based on a set of inertial sensors combination including two miniature gyroscopes and a miniature two-axis accelerometer, which were integrated on a based board to be worn under foot. The sensor signals were sampled at a frequency of 100Hz with a resolution of 14 bits through A/D card, and the sample data is fed into the person computer for the off-line analysis. A fuzzy inference system (FIS) was designed to improve precision of the detection of gait phase. A digital filter is used to remove noise results from the outputs of fuzzy inference system.

Based on the first sensor system for human foot motion analysis of walking, second sensor combination system is developed for human leg segments motion analysis. This second system can be used for synchronous analysis of foot motion analysis, shank motion analysis and thigh motion analysis, in which a new inertial sensor combination and special data-recorder are designed. In experimental study, the leg segments (foot, shank and thigh) angular displacements’ detections are finished successfully on some healthy objects.

For the new method for human motion analysis, it is very important to provide statistical information on the precision and accuracy of the analysis results of our wearable sensor systems as compared to standard method (optical motion analysis method). In the future, it is necessary to perform our studies on a number of different subjects. Furthermore, it is important to show that such a device does not affect the gait of the users.

REFERENCES