DEVELOPMENT OF WEARABLE GAIT EVALUATION SYSTEM
A Preliminary Test of Measurement of Joint Angles and Stride Length

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Abstract: The purpose of this study is to develop wearable sensor system for gait evaluation using gyroscopes and accelerometers for application to rehabilitation, healthcare and so on. In this paper, simultaneous measurement of joint angles of the lower limbs and stride length was tested with a prototype of wearable sensor system. The system measured the joint angles using the Kalman filter. Signals from the sensor attached on the foot were used in the stride length estimation detecting foot movement automatically. Joint angles of the lower limbs and the stride length were measured with reasonable accuracy compared to those values measured with optical motion measurement system with healthy subjects. Joint angle patterns measured in 10m walking with a healthy subject were similar to common patterns. High correlation between joint angles at some characteristic points and walking speed were also found adequately from measured data. The system was suggested to be able to detect characteristics of gait.

1 INTRODUCTION

A motion measurement system has been expected to come into widespread use for evaluation of motor function in rehabilitation training. Although optical motion measurement system is commonly used in research work, the system has shortcomings that measurement condition is limited, costs of the system is very high and so on.

In recent years, inertial sensors such as accelerometers and gyroscopes have been used in measurement and analysis of human movements because of its shrinking in size, low cost and easiness for settings, which are suitable for clinical application. Many studies using inertial sensors have been performed independently in detecting gait phase (Lau and Tong, 2008; Jasiewicz et al., 2006; Selles et al., 2005), measurement of joint angle or segment tilt angle (Tong and Granat, 1999; Dejnabadi et al., 2005; Cikajlo et al., 2008; Findlow et al., 2008), and estimating stride length (Alvarez et al., 2007; Bamberg et al., 2008).

This study aimed to realize simplified wearable gait analysis system using inertial sensors for rehabilitation of motor function, daily exercise for healthcare, and so on. For this purpose, we focused on measurement of lower limb joint angles and stride length simultaneously during gait.

A significant problem on measurement of joint angles with gyroscopes is error accumulation in its integral value caused by offset drift. In order to reduce the offset drift problem of gyroscope, several methods have been proposed: automatic resetting and high-pass filtering (Tong and Granat, 1999), applying Kalman filter to correct shank inclination (Cikajlo et al., 2008), and applying neural network (Findlow et al., 2008). In this study, considering practical use, Kalman filter based joint angle estimation of lower limbs without calibration and resetting during measurement were proposed and tested (Saito et al., 2009).

Stride length is usually estimated from forward acceleration of the foot (Alvarez et al., 2007; Bamberg et al., 2008). In the method, gait events such as heel-off and foot-flat have to be detected to determine integration period for calculating forward movement velocity and forward displacement of the foot. Foot switches or force sensitive registers are sometimes used with inertial sensors for more precise estimation. Other methods of stride length estimation use mathematical model with joint angle of lower limbs or acceleration of a different part of the body (González et al., 2007; Lee et al., 2005). In this study, the forward acceleration of the foot is used to estimate the stride length. A preliminary test showed the feasibility of estimating the stride length

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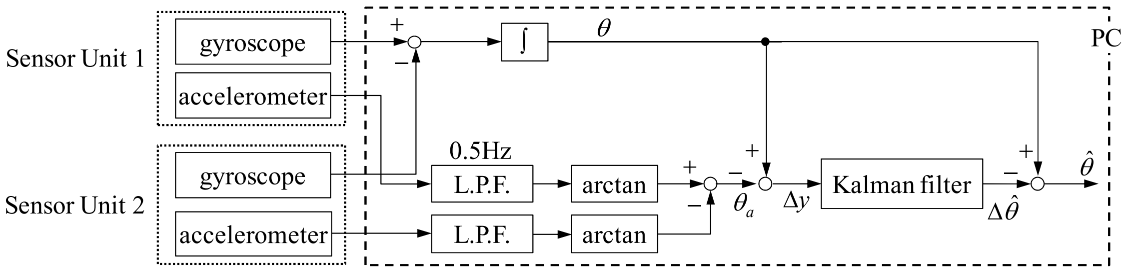

Figure 1: Block diagram of angle measurement system with Kalman filter.

at each step, in which the integration period was determined by detecting stationary state of the foot using the accelerometer (Watanabe et al., 2009).

In order to realize practical gait analysis system, we developed a prototype of joint angle measurement system of the lower limbs (Saito and Watanabe, 2010). In this paper, simultaneous measurement of joint angles and stride length were tested first with the developed system comparing to optical motion measurement system with healthy subjects. Then, the gait parameter measurement was tested in 10m walking with a healthy subject.

2 OUTLINE OF GAIT MEASUREMENT SYSTEM

2.1 Joint Angle Estimation

A joint angle is calculated as integral of difference between angular velocities measured from two gyroscopes, in which the gyroscopes are attached on the adjacent segments. Figure 1 shows the block diagram of joint angle measurement system using Kalman filter. θ and θ_a are joint angles measured with gyroscopes and accelerometers, respectively. Initial joint angle in the integration of angular velocity was determined by the accelerometer. θ_a is calculated from difference of inclination angles of gravitational acceleration of the segments. Outputs of accelerometers were filtered with Butterworth low-pass filter with cut off frequency of 0.5Hz. In the developed system, Kalman filter estimates error of the joint angle measured by gyroscopes $\Delta\hat{\theta}$ from difference between angles obtained by gyroscopes and those by accelerometers Δy. Then, estimated value of joint angle $\hat{\theta}$ is calculated.

The state of the system is represented as the error of the joint angle measured with gyroscopes $\Delta\theta$ and increment of bias offset for one sampling period Δb. That is, the state equation is shown by:

$$\begin{bmatrix}\Delta\theta_{k+1}\\ \Delta b_{k+1}\end{bmatrix}=\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}\begin{bmatrix}\Delta\theta_k\\ \Delta b_k\end{bmatrix}+\begin{bmatrix}w\\ w\end{bmatrix} \tag{1}$$

where w is error in measurement with gyroscopes. Observation equation is given by:

$$\Delta y_k = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\Delta\theta_k\\ \Delta b_k\end{bmatrix}+v \tag{2}$$

where v is error in measurement with accelerometers. Kalman filter repeats corrections (eq. (3)) and predictions (eq. (4)) as follows:

$$\begin{bmatrix}\Delta\hat{\theta}_k\\ \Delta\hat{b}_k\end{bmatrix}=\begin{bmatrix}\Delta\hat{\theta}_k^-\\ \Delta\hat{b}_k^-\end{bmatrix}+\begin{bmatrix}K_1\\ K_2\end{bmatrix}(\Delta y_k-\Delta\hat{\theta}_k^-) \tag{3}$$

$$\begin{bmatrix}\Delta\hat{\theta}_{k+1}^-\\ \Delta\hat{b}_{k+1}^-\end{bmatrix}=\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}\begin{bmatrix}\Delta\hat{\theta}_k\\ \Delta\hat{b}_k\end{bmatrix} \tag{4}$$

where K_1 and K_2 are Kalman gain for $\Delta\theta$ and Δb, respectively. The hat upon a character and the superscript minus represent estimated value and predicted value, respectively. For initial state, $\Delta\hat{\theta}_0^-$ was set at zero and $\Delta\hat{b}_0^-$ was set at the value at the last measurement.

2.2 Stride Length Estimation

The stride length is estimated for each step by the sensor attached on the foot (Figure 2(a)). Tilt angle of the foot in the sagittal plane, $\theta(t)$, is calculated from gyroscope output:

$$\theta(t)=\int_0^t \dot{\theta}(\tau)d\tau+\theta_{init} \tag{5}$$

Here, initial tilt angle θ_{init} is determined by average value of 6 samples of the tilt angle obtained by the accelerometer:

$$\theta_{init}=\frac{1}{6}\sum_{n=0}^{5}\arcsin\left(a_x(n)\big/g\right) \tag{6}$$

The horizontal velocity is calculated under the condition that the x and z axes are in the sagittal plane:

$$v_h(t) = \int_0^t (a_x \cos\theta - a_z \sin\theta) d\tau + v_{init} \qquad (7)$$

Initial value, v_{init}, was set at zero because the integral of sensor signal is calculated during foot movement excluding the stationary state of the foot at the stance phase. In this paper, the stationary state was detected by the accelerometer. That is, the beginning of the step is when the sum of absolute value of acceleration signals of 3-axes is larger than 0.15G for 3 successive samples. The end of the step is detected when the sum of absolute value of acceleration signals of 3-axes is smaller than 0.15G at 3 samples in 10 successive samples. In addition, the gait phase such as heel off, toe off, heel contact and toe contact were also checked automatically during the detection (Minegishi et al., 2010). Then, the calculated velocities of the foot were corrected so as to be 0m/s at the end of the integral by using linear approximation. The movement velocities were assumed to be 0m/s at the beginning and at the end of calculation.

In the above calculation, the sensors should be attached in exact direction of forward movement. For actual use, misalignment of the sensor axis to the traveling direction as shown in Figure 2 (b) was corrected in calculating stride length L using acceleration signal of the y-axis:

$$L = \sqrt{\left(\int_0^T v_h(\tau) d\tau\right)^2 + \left(\int_0^T v_y(\tau) d\tau\right)^2} \qquad (8)$$

2.3 Measurement System

The wearable sensor system consists of seven wireless sensors (WAA-006, Wireless Technologies) and a portable PC (Figure 3). The wireless sensor includes a 3-axis accelerometer, a 2-axis gyroscope and a 1-axsis gyroscope. The sensors are attached on the feet, the shanks and the thighs of both legs, and lumbar region. Acceleration and angular velocity signals of each sensor are measured with a sampling frequency of 100Hz, and are transmitted to PC via Bluetooth network. On the PC, ankle, knee and hip joint angles of both legs are calculated and displayed online. The measured data and calculated angles can be saved on the PC on request. Measurement, recording and joint angle calculation were implemented in Labview (National Instruments). Stride length was calculated offline using Visual Basic.

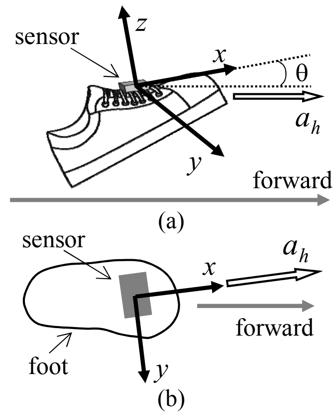

Figure 2: Attachment of sensors on the foot and velocity in forward direction. Side view (a) and top view (b).

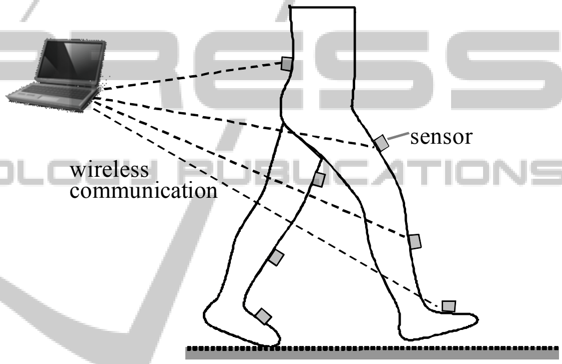

Figure 3: Outline of a prototype of wearable sensor system.

3 EXPERIMENTS

3.1 Evaluation of Measured Parameters

3.1.1 Method

Measurements of hip, knee, and ankle joint angles and stride length were examined in short distance walking with 3 healthy subjects (male, 22-23 y.o.). The wireless sensors were attached on the feet with adhesive tape and on the shanks, thighs and lumbar region with stretchable bands. The optical motion measurement system (OPTOTRAK, Northern Digital Inc.) was used to measure reference data for evaluating calculated joint angles and stride length. The markers for reference data were attached on the left side. The sensor signals and maker positions were measured simultaneously by personal computer with a sampling frequency of 100Hz. The subjects walked on short distance pathway (about 3.6m) at 3 speeds (slow, normal and fast). Five trials were performed for each walking speed started with the left side step. The parameters of Kalman filter were set for each joint angle with trial and error.

3.1.2 Results

Root mean squared error (RMSE) and correlation coefficient (ρ) between measured joint angles and reference values were shown in Figure 4. Values of RMSE were decreased and ρ were increased with the Kalman filtering method.

Figure 5 shows evaluation result of stride length estimation. In each trial, 2 ~ 4 strides were measured with the optical motion measurement system. In some strides, however, the end of stride was not detected automatically by acceleration signals. Those trials were removed from the analysis. Errors for the 1st stride of slow walking were larger than other walking conditions. The errors were less than 10% in average although larger error occurred in some cases, except for the 1st stride of slow walking.

3.2 Measurement in 10m Walking

3.2.1 Method

The developed system was tested in measurement during 10m walking with a healthy subject (male, 23 years old). The wireless sensors were attached on both legs in the same way as shown in the previous section. The subject walked 10m at 3 different speeds (slow, normal, fast). Three trials were performed for each walking speed started with the left side step.

3.2.2 Results

The numbers of steps by both legs were 19, 16 and 12 steps for slow, normal and fast speeds walking, respectively. An example of measured joint angles is shown in Figure 6. The joint angle patterns were similar to common patterns. All the strides were detected automatically by acceleration signal.

In application to rehabilitation or daily exercise, it is required to show measured data simply to physical therapists, patients or users. In this paper, the following ten characteristic points of the joint angles as seen in Figure 6 were analyzed.

1) maximum ankle plantar flexion at stance phase
2) maximum ankle dorsiflexion at stance phase
3) maximum ankle plantar flexion at swing phase
4) maximum ankle dorsiflexion at swing phase
5) maximum knee extension around heel strike
6) knee joint angle at double knee action
7) maximum knee extension around mid stance
8) maximum knee flexion at swing phase
9) maximum hip flexion
10) maximum hip extension

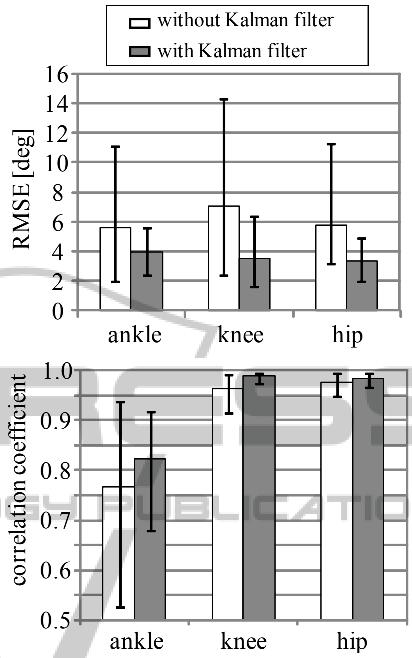

Figure 4: Evaluation results of the joint angle measurement. Average, minimum and maximum values of RMSE and correlation coefficient are shown.

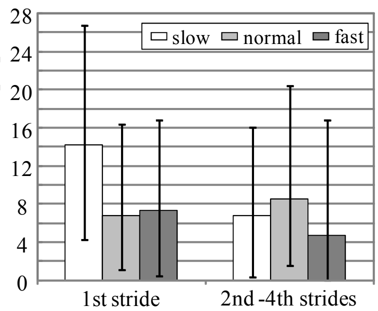

Figure 5: Evaluation results of stride length estimation. Average, minimum and maximum values of absolute error are shown for the 1st stride and from the 2nd strides.

The joint angles at the characteristic points were compared with the instantaneous walking speed that was calculated from the stride length and the time for the stride. In this analysis, the first and the last strides of the left leg and the last one of the right leg were removed since they were different from steady state gait. The joint angles which showed high correlation with the walking speed are shown in Figure 7. Figure 7(f) shows relationship between the

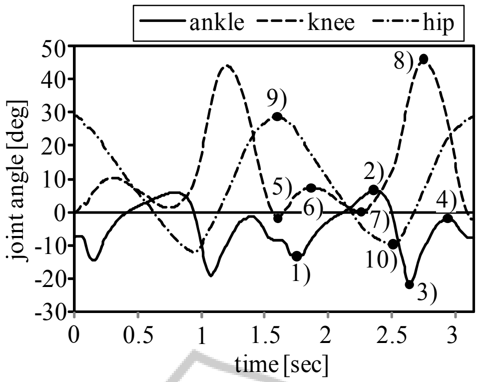

Figure 6: An Example of joint angles for two gait cycles. The numbers on the plots indicate the characteristic points which were analyzed in this paper.

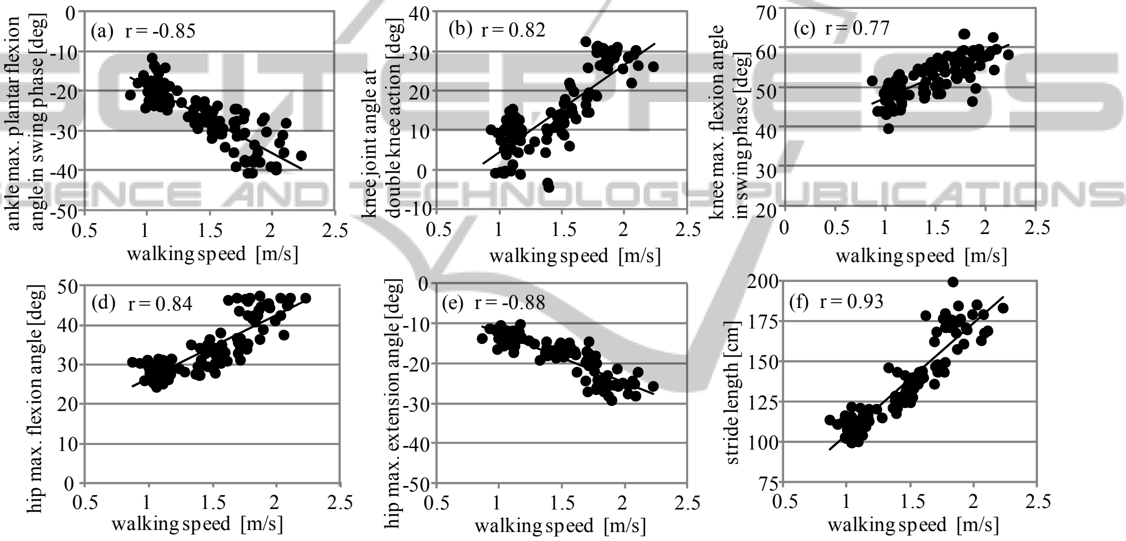

Figure 7: Joint angles at characteristic points that have high correlation with walking speed at each stride. Relationship between the walking speed and the stride length is also shown.

walking speed and the stride length. The result shows high correlation between them.

4 DISCUSSIONS

Joint angles were found to be measured with stable accuracy. Values of RMSE and correlation coefficient were similar to those with our previous sensors (Saito et al, 2009). However, in ankle joint angle measurement, the Kalman filter had smaller effect than other joints. This is considered to be caused by movement of the sensor attached on the foot during dorsiflexion at the stance phase.

Although the absolute errors for the 1st stride of slow walking were large, those for other walking conditions were less than 10% in average. In the stride length estimation, the *x* and *z* axes were assumed to be in the sagittal plane. The integral interval was automatically detected using signals of acceleration. These are considered to affect on the estimation accuracy.

Attachment position of sensors and leg length are considered not to significantly affect measurement accuracy, if the sensors are aligned without rotation. Therefore, attachment positions of the sensors were not exactly regulated, but they were aligned roughly in the frontal plane in the measurements. This simple attachment of sensors is important for clinical applications. However, movement of sensors caused by muscle or tendon movements, misalignment of sensors and so on have to be examined in order to improve estimation accuracy of joint angles and stride length with more subjects.

The measured data in 10m walking showed joint angle patterns that were similar to the common patterns and high correlation between joint angles at some characteristic points and walking speed. The correlations are seemed to be same as relationships which are generally seen in gait of normal subjects. The developed system is suggested to be able to detect characteristics of gait. Other characteristic points are also important for the use in rehabilitation. For example, maximum ankle dorsiflexion in the swing phase can be a practical index for evaluating hemiplegic gait.

5 CONCLUSIONS

A prototype of wireless wearable sensor system was evaluated in simultaneous measurement of joint angles and stride length. The system could measure joint angles of the lower limb and stride length with stable accuracy on healthy subjects. The measured gait patterns were similar to the common pattern and high correlation between joint angles at characteristic points and walking speed were also found adequately with a healthy subject. The developed system is suggested to be able to detect characteristics of gait. Quantitative evaluation will be performed with more subjects for improvement of estimation accuracy. Measurement of gait with motor disabled patients will also be in the next step.

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