LETTER Kalman-Filtering-Based Joint Angle Measurement with Wireless Wearable Sensor System for Simplified Gait Analysis

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SUMMARY The aim of this study is to realize a simplified gait analysis system using wearable sensors. In this paper, a joint angle measurement method using Kalman filter to correct gyroscope signals from accelerometer signals was examined in measurement of hip, knee and ankle joint angles with a wireless wearable sensor system, in which the sensors were attached on the body without exact positioning. The lower limb joint angles of three healthy subjects were measured during gait with the developed sensor system and a 3D motion measurement system in order to evaluate the measurement accuracy. Then, 10 m walking measurement was performed under different walking speeds with a healthy subject in order to find the usefulness of the system as a simplified gait analysis system. The joint angles were measured with reasonable accuracy, and the system showed joint angle changes that were similar to those shown in a previous report as walking speed changed. It would be necessary to examine the influence of sensor attachment position and method for more stable measurement, and also to study other parameters for gait evaluation.

key words: gait analysis, joint angle, gyroscope, Kalman filter, accelerometer

1. Introduction

In rehabilitation of motor function, easy-to-use system for quantitative evaluation of the motor function has been desired. Although an optical 3D motion analysis system and electronic goniometers and so on are commonly used in research works, these systems have some shortcomings for use in rehabilitation: the systems are mainly limited to laboratory use, require inconvenient, time-consuming set up process, are expensive and so on. Therefore, this study focused on measurement of lower limb joint angles during gait with gyroscopes for rehabilitation of motor function and daily exercise for healthcare. Inertial sensors such as accelerometers and gyroscopes are suitable for the measurement of human movements as a wearable sensor system because of its shrinking in size and cost.

Measurement of inclination angles of body segments or joint angles has been studied using inertial sensors [1]– [8]. However, a significant problem of measurement with gyroscopes is error accumulation in the integral of sensor output, which is caused by offset drift of gyroscope. In order to reduce the influence of the offset drift, an automatic resetting of the angle in each gait cycle and high-pass filtering were applied [1]. Joint angle estimation by the neural network was also reported [6]. Those methods, however, were not suitable for the rehabilitation because of large variety of gait of patients and needs of dc and low frequency information of angle data.

Kalman filter can be applied to solve this problem. We showed effectiveness of the Kalman filtering based joint angle measurement on the knee and ankle joints [5], [9]. The Kalman filter was also effective in correcting measured shank inclination angle [4] and knee joint angle [8]. However, joint angle measurement using the Kalman filter has not been evaluated sufficiently considering clinical applications. That is, in those previous studies, the Kalman filtering method was not tested in simultaneous measurement of hip, knee and ankle joint angles and sensor attachment method was not suitable for clinical applications. It is desirable to attach the inertial sensors without exact positioning because simplified preparation is required in practical clinical applications.

In this paper, a wireless wearable sensor system was developed for a feasibility test considering practical clinical applications. A Kalman filtering based joint angle measurement method was examined with the developed system in measurement of the lower limb joint angles during gait comparing to reference angles obtained from an optical motion analysis system. The measurements were performed with healthy subjects by attaching the sensors on the body without exact positioning. The joint angles were also measured in 10 m walking under different walking speeds in order to test whether the developed system can detect the difference in walking or not.

2. Wireless Wearable Sensor System

2.1 Joint Angle Measurement Using Kalman Filter

A joint angle is calculated as an integral of difference between outputs of two gyroscopes as shown in Eq. (1), in which the sensors are attached on adjacent body segments:

$$\theta = \int (\omega_1 - \omega_2) dt + \theta_0 \tag{1}$$

where ω_1 and ω_2 shows angular velocities measured with gyroscopes attached on adjacent segments such as the thigh and the shank for knee joint angle calculation. θ_0 is the initial joint angle which can be determined from outputs of accelerometers. The calculated angles are corrected by the Kalman filter shown in Fig. 1. θ is the joint angle measured

Manuscript received December 3, 2010.

Manuscript revised April 7, 2011.

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DOI: 10.1587/transinf.E94.D.1716



Fig. 1 Block diagram of the joint angle measurement using the Kalman filter.

with gyroscopes. θ_a is the joint angle measured with accelerometers, which is calculated from difference of inclination angles of the segments measured by using inclination of gravitational acceleration. The acceleration signals were filtered using Butterworth low-pass filter with the cut off frequency of 0.5 Hz in order to reduce acceleration of movement. In Fig. 1, the Kalman filter estimates the error of the joint angle measured with gyroscopes $\Delta \hat{\theta}$ from difference Δy between the angle obtained by gyroscopes and that by accelerometers. Then, estimated joint angle $\hat{\theta}$ is calculated by subtracting $\Delta \hat{\theta}$ from θ .

The state equation of the system is represented as the error of the joint angle measured with gyroscopes $\Delta\theta$ and bias offset of outputs of gyroscopes Δb as follows:

$$\begin{bmatrix} \Delta \theta_{k+1} \\ \Delta b_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta b_k \end{bmatrix} + \begin{bmatrix} \Delta t \\ 1 \end{bmatrix} w \tag{2}$$

where Δt is the sampling period, w is error in measurement with gyroscopes. Observation signal of the system is the deference of two sensors, which is given by:

$$\Delta y_k = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \Delta b_k \end{bmatrix} + v \tag{3}$$

where v is error in measurement with accelerometers. On this state-space model, the Kalman filter repeats corrections (Eq. (4)) and predictions (Eq. (5)):

$$\begin{bmatrix} \Delta \hat{\theta}_k \\ \Delta \hat{b}_k \end{bmatrix} = \begin{bmatrix} \Delta \hat{\theta}_k^- \\ \Delta \hat{b}_k^- \end{bmatrix} + \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} (\Delta y_k - \Delta \hat{\theta}_k^-)$$
(4)

$$\begin{bmatrix} \Delta \hat{\theta}_{k+1}^- \\ \Delta \hat{b}_{k+1}^- \end{bmatrix} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \hat{\theta}_k \\ \Delta \hat{b}_k \end{bmatrix}$$
(5)

where K_1 and K_2 are Kalman gains for $\Delta\theta$ and Δb , respectively. Notations such as $\Delta\hat{\theta}$ and $\Delta\hat{\theta}^-$ represent estimated value and predicted value for $\Delta\theta$, respectively. As the initial state, $\Delta\hat{\theta}_0^-$ was set 0 and $\Delta\hat{b}_0^-$ was set $\Delta\hat{b}$ at the last measurement. In this paper, the steady-state Kalman filter was applied instead of the standard Kalman filter.

2.2 System Configuration

The wearable sensor system consists of seven wireless sensors (WAA-006, Wireless Technologies) and a portable PC (Fig. 2). The wireless sensor includes a 3-axis accelerometer, a 2-axis gyroscope and a 1-axis 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



Fig. 2 Outline of the developed wearable sensor system.

frequency of 100 Hz, 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).

3. Experimental Methods

3.1 Evaluation Experiment of the System

Measurements of hip, knee, and ankle joint angles were examined with 3 healthy subjects (male, 22–23 y.o.). The wireless sensors for the feet were attached on shoes with adhesive tape and those for the shanks, thighs and lumbar region were done on the each part by stretchable bands with hook and loop fastener. The sensors were put inside pocket of the band. Here, considering practical clinical application, attachment positions of the sensors were not determined exactly, but aligned roughly in the frontal plane.

The subjects walked on pathway (about 3.6 m) at 3 different speeds (slow, normal and fast). These speeds were controlled by subjects themselves. Five trials were performed for each walking speed started with the left side step. The optical motion measurement system (OPTO-TRAK, Northern Digital Inc.) was used to measure reference data for evaluating measured joint angles. The markers of the 3D motion measurement system for reference data were attached on the left side. The sensor signals and maker positions were recorded by a personal computer with a sampling frequency of 100 Hz.

The parameter values of the Kalman filter were determined by a trial and error method and fixed for all measured data in evaluation. There were offset difference in the measured joint angles between the sensor system and the 3D motion measurement system because the markers for the reference signals could not be attached on the sensors. Therefore, the difference in joint angles were removed for evaluation of the method only at the beginning of the 1st measured data by using mean value of the first 100 samples. Then, root mean squared error (RMSE) and correlation coefficient (ρ) between the estimated joint angles and the reference values were calculated.

3.2 Measurement in 10 m Walking

The system was tested in 10m walking measurement with a healthy subject (male, 23 y.o.). At first, joint angles were measured during quiet standing after attaching the sensors and the measured angles were set as 0 deg. Then, joint angle measurements in 10m walking were performed under 3 different walking speeds (slow, normal and fast). The walking speeds were controlled by the subject. Three trials were performed for each walking speed started with the left side step. Measurement results were compared between different walking speeds to examine feasibility of the system in detecting deference of gait. The angles at the first two gait cycles and the last two gait cycles were excepted from the analysis in order to evaluate steady state walking.

4. Results

4.1 Evaluation Experiment of the System

An example of measured joint angles is shown in Fig. 3. It is shown that the Kalman filtering based method could measure the joint angles adequately during gait, while difference between the reference angles and those angles calculated by only using outputs of gyroscopes increased with time. The errors caused in the integral of outputs of gyroscopes because of their offset drift were reduced by the Kalman filter. Measured joint angle patterns were similar to those such as seen commonly in other literatures.

Average values and standard deviations of the RMSE and the correlation coefficient (ρ) were shown for each joint of each subject in Table 1. Walking speed of subject 1, 2 and 3 were approximately $0.60 \sim 1.12 m/s$, $0.42 \sim 1.25 m/s$ and $0.78 \sim 1.33 m/s$, respectively. Average values of the RMSE and ρ were improved by the Kalman filtering method. The RMSE values were smaller than about 5 deg for all joint angles and ρ were larger than about 0.98 for the knee and the hip joint angles and larger than about 0.8 for the ankle joint angle. Variations of those parameter values between measurement trials were also decreased, and the variations were relatively small although the average values were calculated from measured data under various walking speeds.

4.2 Measurement in 10 m Walking

In the 10*m* walking test, the number of steps of both legs were 19, 16 and 12 for the slow, normal and fast speed walking, respectively. Calculated walking speeds were approximately $0.61 \sim 0.63 m/s$, $0.84 \sim 0.87 m/s$ and $1.35 \sim 1.41 m/s$ for the slow, normal and fast speed walking, respectively. Since all the trials indicated similar joint angle pattern as seen in Fig. 3, extreme values of each joint angle were compared between different speed walkings. Figure 4 shows re-



Fig.3 An example of measured joint angles with and without the Kalman Filter (KF) (normal speed, subject 1). Positive values show ankle dorsiflexion angle and flexion angles of the knee and the hip.

		RMSE (deg)		ρ	ρ	
		without KF	with KF	without KF	with KF	
Ankle	Subject 1	2.84 ± 0.86	3.04 ± 0.48	0.909 ± 0.027	0.892 ± 0.019	
	Subject 2	7.05 ± 1.84	4.48 ± 0.59	0.718 ± 0.089	0.792 ± 0.045	
	Subject 3	6.92 ± 1.40	4.31 ± 0.76	0.676 ± 0.091	0.787 ± 0.055	
	Mean	5.60 ± 2.42	3.94 ± 0.89	0.768 ± 0.126	0.824 ± 0.064	
Knee	Subject 1	4.20 ± 1.38	2.60 ± 0.75	0.975 ± 0.007	0.991 ± 0.002	
	Subject 2	4.73 ± 1.37	2.83 ± 0.52	0.976 ± 0.013	0.991 ± 0.003	
	Subject 3	12.16 ± 1.86	5.22 ± 0.78	0.945 ± 0.017	0.984 ± 0.005	
	Mean	7.03 ± 3.95	3.55 ± 1.37	0.965 ± 0.019	0.989 ± 0.005	
Hip	Subject 1	7.17 ± 2.67	2.90 ± 0.28	0.971 ± 0.011	0.987 ± 0.005	
	Subject 2	5.74 ± 1.51	3.40 ± 0.80	0.983 ± 0.011	0.991 ± 0.002	
	Subject 3	4.28 ± 0.52	3.70 ± 0.94	0.975 ± 0.008	0.978 ± 0.008	
	Mean	5.73 ± 2.15	3.33 ± 0.80	0.976 ± 0.011	0.985 ± 0.008	

Table 1 Comparison of evaluation results between with and without the Kalman filter (KF).



Fig. 4 Joint angle changes at characteristic points as the waking speed changed in 10m walking measurement. Positive values show ankle dorsiflexion angle and flexion angles of the knee and the hip.

lationships between some joint angles and walking speed conditions. The selected joint angles were the maximum hip flexion and extension angles, the knee joint angle at the double knee action, the maximum knee flexion angle in the swing phase, and the maximum plantar flexion of the ankle in the swing phase. As seen in Fig. 4, the developed system showed that the joint angles increased as walking speed increased. There were no clear differences in other extreme values between walking speed conditions.

5. Discussion

In this study, attachment positions of the sensors were not exactly regulated, but they were aligned roughly in the frontal plane in the measurements. This simple sensor attachment method is important for practical clinical applications. Generally, in order to realize high measurement accuracy, exact positioning of sensors or measurement of sensor positions are required [2], [8]. It is considered that these initial settings or calibration process severely affect practical use of the sensor system. It may be difficult to determine sensor positions for high measurement accuracy with patients, because a length of time of rehabilitation training is limited. Therefore, just attaching sensors such as the method 1719

of this study is a preferable preparation for the measurement.

Considering the practical sensor attachment method, RMSE smaller than 5 deg and correlation coefficient larger than 0.95 were targeted in this study based on previous works [1], [3], [6], [7]. The Kalman filtering based measurement method stably reduced joint angle error and increased correlation coefficient almost achieving the target values, even if walking speeds or subjects were different. In the previous studies that did not require any special equipments for calibration and time-consuming set up process, the RMSE was 6.42 deg and the correlation coefficient was 0.93 for knee joint angle measurement [1], mean RMSE values were 8.72 deg and 6.79 deg and mean correlation coefficients were 0.88 and 0.92 for hip flexion/extension angle and knee joint angle, respectively [7]. It is considered that the developed system in this study achieved good accuracy considering practical application as a simple gait analysis system.

Since errors caused by the offset drift of gyroscope outputs varied between measurement trials, the Kalman filter would be effective. However, values of the RMSE for ankle joint angle with subjects 2 and 3, and knee joint angle with subject 3 were large a little bit. The correlation coefficient with subjects 2 and 3 were small for ankle joint angle. In those results, since values of the RMSE and ρ were significantly deteriorated without the Kalman filter, problems are considered not to be in the Kalman filter. Although the sensors were attached on the body paying attention to the direction of sensor axes in the frontal plane, movement of the sensors caused by muscle or tendon movements, misalignment of sensors and so on are considered to affect measurement accuracy. In addition, there is a possibility of using other Kalman filtering methods or methods of resetting the offset drift. Those have to be examined in order to improve measurement performance.

One of dominant causes for the offset drift of gyroscope is temperature drift. A way of handling it is to use temperature sensors and temperature offset tables. In this study, however, the Kalman filtering method was used because it had an advantage of using only sensors for movement measurement. That is, extra sensors are not required. In addition, it was necessary to reduce the amount of transmitting data in wireless communication. The method of using the temperature sensor can be an option in 3D movement measurement.

It has not been made clear yet how high measurement accuracy of the sensor system is required in rehabilitation training. Therefore, 10 m walking measurements under the different walking speeds were performed and the developed system was tested in detecting differences of the walkings. As shown in Fig. 4, the developed system showed that faster walking speed increased joint angles at some points. The number of steps decreased as the walking speed increased in the measurement results. That is, step length increased in faster speed walking, and then joint angles increased as shown in Fig. 4. These changes between different speed walkings were similar results as those shown in a previous study [10]. Therefore, the developed system is suggested to have reasonable measurement accuracy to detect characteristics of different walking, and to become effective in rehabilitation training.

This study focused on measurement of joint angles in the sagittal plane. For more detailed evaluation, however, it is desirable to measure abduction and adduction angles and internal and external rotation angles. The internal and external rotation angle can not be measured with the current method. In addition, it is not easy to measure internal and external rotation angles even with a 3D motion measurement system. Therefore, the simple gait analysis with the wearable sensors will target to measure abduction and adduction angles. On the other hand, other parameters such as gait event, stride length, walking speed are very useful for gait evaluation. Other measurement methods of various parameters have to be tested with the developed sensor system.

6. Conclusion

In this paper, the wireless wearable sensor system for simplified gait evaluation was developed implementing the Kalman filtering based joint angle measurement method. Hip, knee and ankle joint angles were measured simultaneously during gait with the developed system, in which the sensors were attached on the body without exact positioning. The Kalman filtering based method successfully reduced joint angle error caused by offset drift of gyroscope. The joint angles were measured reasonably with the developed wearable sensor system under different walking speed conditions on different subjects. The system could also show changes in some joint angles between different speed walkings measured during 10 m walking, which were similar to the results as shown in a previous study. Attachment position and method of sensors would be examined for more stable measurement, and also other parameters for gait evaluation have to be studied with the developed system.

Acknowledgement

This work was supported in part by Miyagi Prefectural Gov-

ernment under the Sendai Advanced Preventive Health Care Services Cluster, and the Ministry of Education, Culture, Sports, Science and Technology of Japan under a Grant-in-Aid for Scientific Research (B).

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