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# Tests of Wireless Wearable Sensor System in Joint Angle Measurement of Lower Limbs

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*Abstract*— **The aim of this study was to test the wireless wearable sensor system consists of inertial sensors considering application to rehabilitation. The sensor system was evaluated in measurement of hip, knee and ankle joint angles with healthy subjects comparing to those measured with a 3D motion measurement system. Then, the lower limb joint angles of elderly subjects including paralyzed subjects were measured during gait on the level floor with the sensor system. Evaluation of measured joint angles in comparison with the motion measurement system showed that mean values of the RMSE were smaller than 4 deg for all the joint angles, and mean values of the correlation coefficient were larger than 0.985 for hip and knee joint angles and about 0.90 for ankle joint angle. In measurement with elderly subjects, the sensor system showed some differences in joint angles between the paralyzed and the non-paralyzed sides.**

## I. Introduction

Motor functions of lower limbs are important in order to prevent bedridden and to make independence in daily living and social participation. In this study, a wearable sensor system has been studied aiming to support motor rehabilitation of patients with a motor impairment, motor training in health care and exercise instruction of elderly persons. In the rehabilitation of motor function, a therapist generally evaluates a level of motor function by simple methods such as watching movements, measurement of time for a task, counting the number of steps.

Quantitative measurements of movements with a motion measurement system are considered to be effective in rehabilitation training. An optical 3D motion analysis system and electronic goniometers and so on are commonly used in research works. However, these systems have some shortcomings for using in rehabilitation: most systems are for laboratory use, require time-consuming setup process, expensive, and so on.

Inertial sensors such as accelerometers and gyroscopes can be useful in measurement and analysis of movements in rehabilitation because of its shrinking in size, low cost and easiness for settings, which are suitable for clinical application. For application of the inertial sensors to gait analysis, detecting gait phase [1, 2], measurement of joint angle or segment tilt angle [3-7], and estimating stride length [8, 9] and so on were studied. However, measurement of total lower limb movements such as simultaneous measurement of hip, knee and ankle joint angles has not been studied sufficiently with an inertial sensor system considering clinical applications [5]. Therefore, in this study, simple gait evaluation system was focused. In order to realize a practical system, a wireless wearable sensor system was developed and examined in measurements of gait of healthy subjects [10].

In this paper, the sensor attachment method was modified and evaluated with neurologically intact subjects. Then, the system was examined clinically in measurement of walking on the level floor with elderly subjects including hemiplegic subjects in order to find the effectiveness of the wearable sensor system.

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## II. Methods

### A. Joint Angle Measurement System

The wireless wearable sensor system consists of seven wireless sensors (WAA-006, Wireless Technologies) and a portable PC (Fig. 1). The wireless sensor can measure 3-axis components of angular velocity and acceleration. The sensors are attached on the feet, the shanks and the thighs of both legs, and lumbar region with stretchable bands with hook and loop fastener. The sensors are put inside of pocket of the band. Acceleration and angular velocity signals of each sensor are measured with a sampling frequency of 100Hz, and are transmitted to PC via Bluetooth network.

Ankle, knee and hip joint angles of both legs are calculated from the measured data and displayed on the PC.

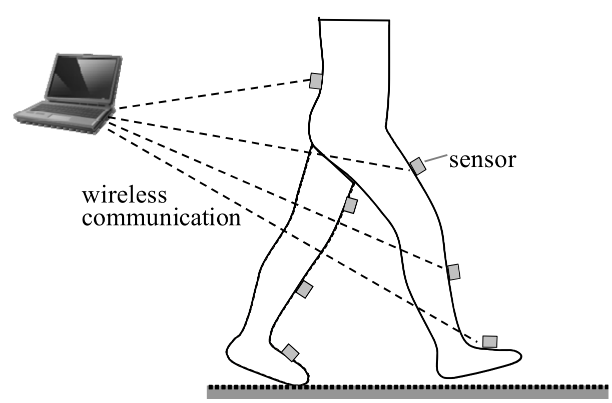



Fig. 1 Outline of the wireless lower limb joint angle measurement system.

The measured and the calculated angle data are recorded on the PC by selecting the save mode before measurement. The saved data can be displayed offline after the measurement as plots of joint angles with respect to time or a stick figure animation.

Lower limb joint angles are calculated basically as integral of difference between angular velocities measured from two gyroscopes, in which the gyroscopes are attached on the adjacent segments. That is,

$$\theta = \int (\omega_1 - \omega_2)dt + \theta_0$$

where $\omega_1$ and $\omega_2$ are angular velocities measured with the gyroscopes. $\theta_0$ is initial joint angle that are determined from acceleration data in the sagittal plane ($g_x$ and $g_z$) as follows.

$$\theta_0 = \tan^{-1} g_{z1}/g_{x1} - \tan^{-1} g_{z2}/g_{x2}$$

The calculated joint angle is corrected by Kalman filter using joint angle measured with accelerometers [10]. 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 ($\Delta y$). 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 ($\Delta b$). That is, the state equation is shown by:

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

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

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

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

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

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

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

The measurement, calculation, display and recording were implemented in Labview (National Instruments), and the stick figure animation was implemented in C#.

### B. *Evaluation of Joint Angle Measurement*

Measurements of hip, knee, and ankle joint angles were examined in short distance walking with 3 healthy subjects (male, 22-23 y.o.). The optical motion measurement system (OPTOTRAK, Northern Digital Inc.) was used to measure reference data for evaluating calculated joint angles.

The subjects wore a gym sleeveless shirt, gym half tights and running shoes. The sensors were attached on the clothes or on the skin, and on the shoes with the stretchable band. The markers for reference data were attached on the left side. The sensor signals and maker positions were measured simultaneously by a 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.

### C. *Measurement with Elderly Subjects*

Lower limb joint angles were measured during walking on the level floor with the wireless wearable sensor system with three elderly subjects (subject A: 77 y.o. male, subject B: 71 y.o. male with left hemiparesis, and subject C: 68 y.o. male with mild right hemiparesis). The sensors were attached on their own clothes and shoes with the stretchable bands. After the sensors were attached on each segment of the subject, joint angles were measured during quiet standing and the measured angles were set as 0 deg. Then, the subject walked on the floor with his own pace. Three measurement trials were performed for each subject.

## III. Results

### A. *Evaluation of Joint Angle Measurement*

An example of measured joint angles is shown in Fig. 2.

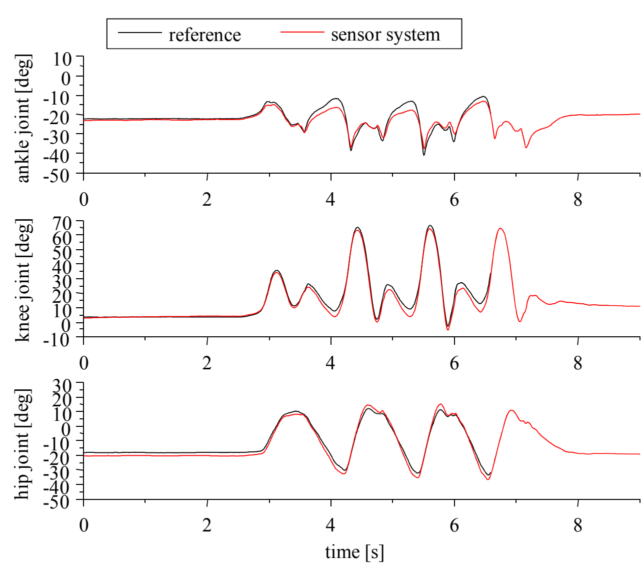



Fig. 2 An example of measured joint angles of the left leg with the sensor system and the 3D motion measurement system (normal speed). Positive value shows ankle dorsiflexion angles, and knee and hip flexion angles.

Since the measurement area of the 3D motion measurement system is about a width of 3.6 m, reference data are shorter than the data measured with the sensor system. The sensor system could measure the joint angles appropriately. The measured angle patterns of the normal subjects are similar to those seen in other papers.

Root mean squared error (RMSE) and correlation coefficient (ρ) between measured joint angles and reference values are shown in Fig. 3. Values of RMSE were decreased and ρ were increased with the Kalman filtering method. Average values of the RMSE were smaller than 4 deg for all joint angels at all walking speeds. Average values of ρ were large for the knee and the hip joint angels at all the walking speeds (larger than 0.985). For the ankle joint angle, however, ρ was a little bit small compared to other measured data (about 0.90).

### *B. Measurement with Elderly Subjects*

Figure 4(a) shows an example of measurement with a subject. Attachment of the sensors on the body and preparation for measurement were very simple, which completed within a few minutes. There were no problems in measurements with the sensor attachment method.

An example of measured joint angles with the subject is shown in Fig. 4(b). Because of the left hemiplegic subject, some differences in joint angles between the left and the right sides are found from the measured joint angles. For example, for the paralyzed side, dorsiflexion angle during the stance phase and plantar flexion angle at the heel off were small. Knee flexion angle during the swing phase was small and the small flexion position lasted for about 0.5 s with the hip flexion. Hip flexion/extension angles were also small.

An image of the stick figure animation is shown in Fig. 5. The point of sight can be changed by using the left or the right arrow keys. The measured data were presented by the stick figure animation to each subject after the measurement. The subjects could find some characteristics of their walkings

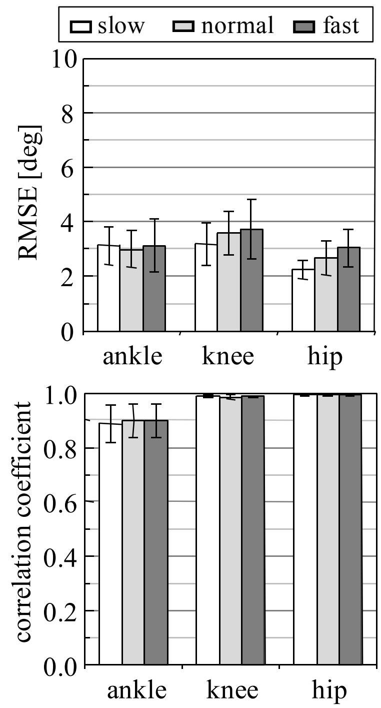
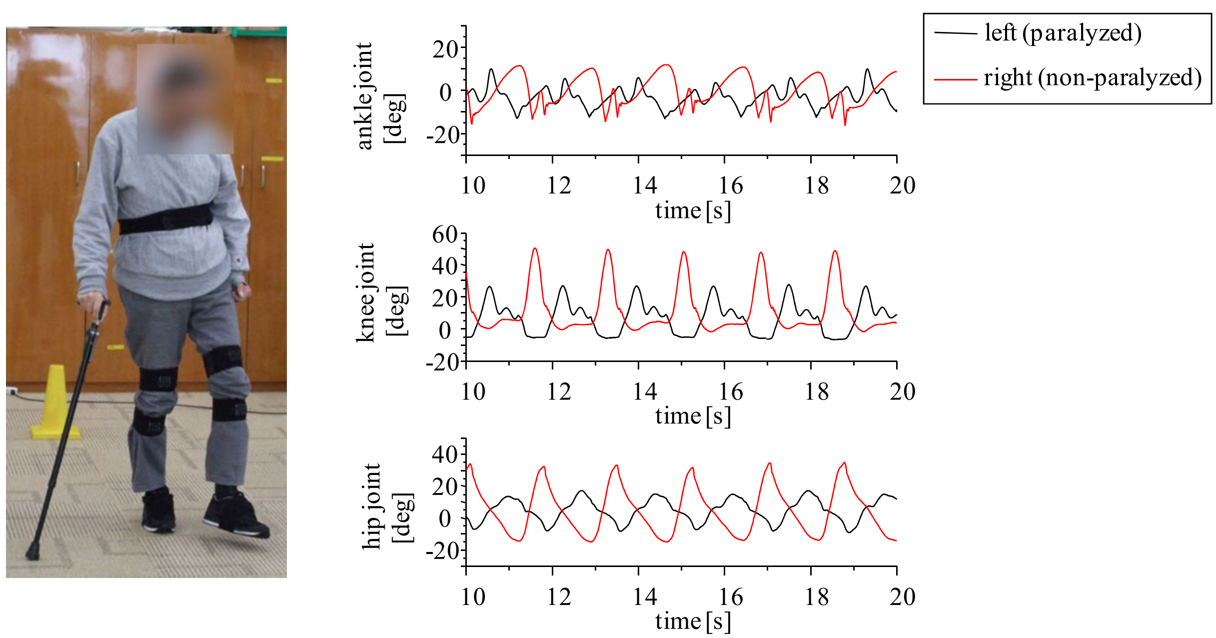



Fig. 3 Evaluation results of the wearable sensor system with healthy subjects. Average values and standard deviations of the RMSE and the correlation coefficient between the sensor system and the 3D motion measurement system are shown.




(a) (b)

Fig. 4 An example of measurement with the elderly subject. A picture for the measurement (a) and measured joint angles (b) are shown (Subject B with left paralisys). Positive values of the joint angles show flexion of the hip and the knee joint and dorsiflexion of the ankle joint.

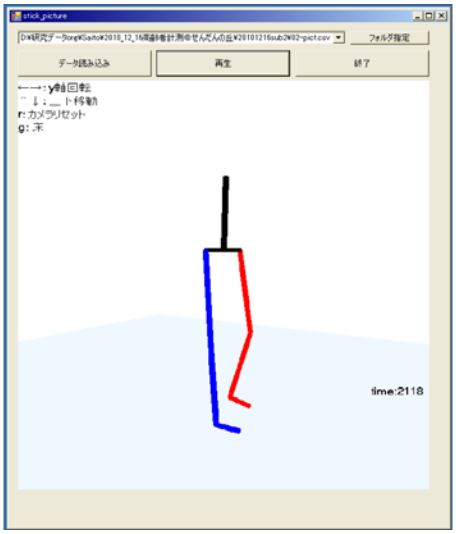



Fig.5 An image of the stick figure animation (Subject A)

from the animation.

## IV. Discussions

The sensor attachment method to the feet in this paper was modified from our previous study [10]. The average RMSE and ρ for the ankle joint angle were improved to 3.08 deg from 3.94 deg and to 0.893 from 0.824, respectively. For short time measurement such as in rehabilitation, the stretchable band can be effective in the attachment of the sensors on the shoes. However, in some trials, the RMSE values were larger than 4 deg and the CCs were smaller than 0.9. It is considered that the measurement accuracy is acceptable because other methods using simplified calibration process showed that RMSE was between 6 and 9 deg and CC was between 0.88 and 0.93 [3, 7]. However, measurement of the joint angles has to be studied in more detail in order to stabilize measurement accuracy.

From the measurement with elderly subjects, the sensor system could show some characteristics of walking. Especially, the measured joint angles of the hemiplegic subject showed clearly differences between the non-paralyzed and the paralyzed sides. In our previous study with a healthy subject, differences in joint angles between different speed walkings were shown from measured joint angles with the sensor system [10]. It is considered that measurement accuracy of the sensor system is reasonable.

In order to use the sensor system clinically, 0 deg has to be set appropriately. In the measurements with the elderly subjects, the measured data during standing were set to 0 deg because initial angles at quiet standing measured with accelerometers do not show appropriate angles because of the human 3-D shape and are different between subjects. The measurement for setting 0 deg was very simple and can be effective in clinical application. However, there was no support in the measurement of this paper to keep appropriate upright position such as 0deg between the trunk and the thigh, full extension of the knee joint, and 90 deg between the shank and the foot. Therefore, meaning of 0 deg may be different between subjects in the results.

The stick figure animation was effective to present measured gait to the subject. In the animation, inclination angle of the trunk was also used. It was possible to find relationship between those angles. Currently, the sensor system can also show the plots of joint angles of the hip, the knee and the ankle with respect to time. It is desirable to analyze comprehensively including inclination angles of body segments, gait event timing, and stride length and so on. It will also be desired to decrease the number of sensors considering required gait parameters in clinical evaluation.

## V. Conclusion

The wireless wearable sensor system was evaluated in measurement of lower limb joint angles with healthy subjects comparing to those measured with a 3D motion measurement system. Then, the lower limb joint angles of elderly subjects were measured during walking on the level floor with the sensor system. The sensor system could measure joint angles with acceptable accuracy and show characteristics of gait. It is expected that joint angle measurement with the sensor system can be effective in rehabilitation clinically. It will become more effective by including other gait parameters.

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