A Validation Test of Measurement Method of Lower Limb Angles Based on Kalman Filter on Different Type of Inertial Sensors

Yuta Teruyama and Takashi Watanabe

***Abstract*—Lower limb joint angle measurement method based on Kalman filter was tested using commercially available inertial sensors in our previous study for a rehabilitation use. Although the angle measurement method was effective, measurement with the wireless sensors were affected by wireless communication environment. Wired and wireless inertial sensor systems were developed in our laboratory for solving the wireless communication problem. This paper aimed to examine the 2 developed sensors, since those were different from the previously used sensors in data communication system or resolution in measurement. The 2 developed sensors and 2 commercially available sensors were evaluated in measurements of inclination and joint angles of a rigid body model comparing to the results of an optical motion measurement system. The angles were measured by correcting the angles calculated from outputs of gyroscopes based on a Kalman filter using outputs of accelerometers. All of the sensors showed small RMS errors under the static and dynamic conditions. The results suggested that various inertial sensors could measure inclination and joint angles stably if angles are calculated by using the Kalman filtering based method. It would be possible to replace sensors with inexpensive or latest commercially available sensors.**

***Index Terms*—Lower limb, angle, inertial sensor, kalman filter.**

I. Introduction

Motion measurement with optical 3D motion measurement system or electric goniometers can be effective for objective and quantitative evaluation in rehabilitation of motor function. However, these systems have some shortcomings in that the set-up of these systems are not easy, measurement condition is limited and costs of these systems are very high. Therefore, many studies have been performed in measurement of lower limb joint angles and stride length and so on with inertial sensors such as a gyroscope and an accelerometer, which are small, low cost and easy for settings [1]- [9].

In our previous study, a method of measuring lower limb joint angles using commercially available wireless inertial sensors was developed to realize simplified wearable gait evaluation systems for rehabilitation support [10]. The inertial sensors used in the test, however, had a problem in measurements that was affected by wireless communication environment. Since measurement range of the used inertial sensor was within about 10*m* (Bluetooth class 2), it was expected to be replaced with the sensor which enables long distance measurement.

Wired sensors and wireless sensors with memory were newly developed in our research group with the goal of stable measurement. In this paper, the two newly developed inertial sensors were tested in measurements of angles comparing to results of commercially available sensors. Basically, measurement accuracy with Kalman-filtering-based angle calculation is expected not to vary between those sensors. However, it is necessary to make clear the similar accuracies of those sensors with the Kalman filtering method, because rapid technical improvement in recent years will provide inexpensive or smaller sensors, and then senor modules will be replaced by the latest one. Therefore, in this paper, the two newly developed inertial sensors and two commercially available inertial sensors were tested in angle measurement using a rigid body model.

II. Angle Measurement Method

The inclination angles of body segments are calculated by integrating outputs of gyroscopes. The joint angles are calculated from difference of inclination angles of the adjacent segments. The integration error is corrected by Kalman filter using the angles calculated from the outputs of the accelerometers (Fig. 1).

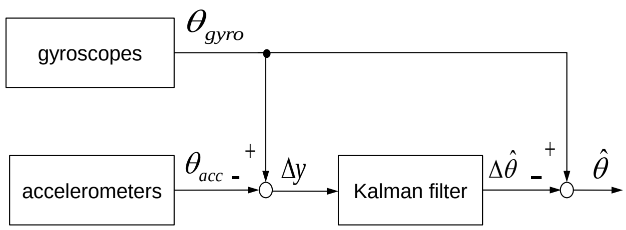

Fig. 1. Block diagram of the angle calculation method using Kalman Filter.

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

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

where w is error in measurement with gyroscopes. Δt is sampling period. Observation signal is the deference of

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angles obtained from a gyroscope and an accelerometer Δy, which is given by:

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

where v is error in measurement with accelerometers. On this state-space model, Kalman filter repeats corrections (Eq. (3)) and predictions (Eq. (4)):

TABLE I: INERTIAL SENSORS USED IN MEASUREMENT TEST

	Communication and Recording system	Accelerometer, Gyroscope	Sensitivity per LSB	Sensor size
Sensor 1 -wireless	Bluetooth (WAA-006, Wireless Technologies)	±4 G (H30CD, Hitachi Metals) x-axis, y-axis： ±500 deg/s (IDG-400，Inven Sense) z-axis： ±300 deg/s (XV-3500CB，Epson Toyocom)	Accelerometer： 2mG Gyroscope :x-axis, y-axis: 1.46dps,z-axis: 4.37dps	39×44×12mm 20g
Sensor 2 -wired	Logger (micro SD)，108×22×55mm，about 117g	±4 G (ADXL345, Analog Devices) x-axis, y-axis: ±440 deg/s (IDG-650, Inven Sence) z-axis： ±440 deg/s (ISZ-650, Inven Sense)	Accelerometer: 7.8125mG Gyroscope: 1.2057dps	32×32×10mm about 33g
Sensor 3 -wireless	2.4GHz Wireless communication module	±6 G (AH-6120LR, Epson Toyocom) ±1000 deg/s (AH-6120LR, Epson Toyocom)	Accelerometer:14.66mG Gyroscope: 3.23dps	40×40×10mm about 20g
Sensor 4 -wireless	Bluetooth(WAA-010, Wireless Technologies)	±4 G (Analog Devices) ±2000 deg/s (Inven Sense)	Accelerometer： 4mG Gyroscope: 0.1dps	39×44×12mm,20g

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

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

where K_1 and K_2 are Kalman gain for $\Delta\theta$ and Δb. Notations such as $\Delta\hat{\theta}$ and $\Delta\hat{\theta}^-$ represent estimated value and predicted value for $\Delta\theta$, respectively. For the initial condition, $\Delta\hat{\theta}_0^-$ was set 0 and $\Delta\hat{b}_0^-$ was set $\Delta\hat{b}$ at the last measurement. The Kalman filter was applied repeatedly until its outputs converged.

III. EXPERIMENTAL METHOD

Four different inertial sensors which had differences as shown in Table I were tested in angle measurement. All of sensors can measure 3-axis angular velocities and accelerations. Sensor 1 and Sensor 4 are commercially available wireless sensors, which transmit data to PC via Bluetooth network (class 2, communication range is within about 10*m*). Sensor 4 is the replacement of Sensor 1, in which resolutions of gyroscope and accelerometer has been changed. Sensor 2 and Sensor 3 were developed in our laboratory. Sensor 2 is a wired sensor that records signals to micro SD of the logger, in which a replacement of the gyroscope in Sensor 1 was used. Resolution of Sensor 2 was different from Sensor 1. Sensor 3 was also developed in our laboratory, which transmitted measured data to PC via 2.4*GHz* wireless communication (communication range is within about 30*m*). Resolutions of the gyroscope and the accelerometer of Sensor 3 were lower than other 3 sensors.

The angles measured with the sensors were compared to the angles measured with optical 3D motion measurement system (OPTOTRAK, Northern Digital Inc.). OPTOTRAK markers and the sensors were attached on a rigid body model as shown in Fig. 2. The rigid body model simulates the motion of the thigh, the shank, and the knee joint, while the hip joint position is fixed.

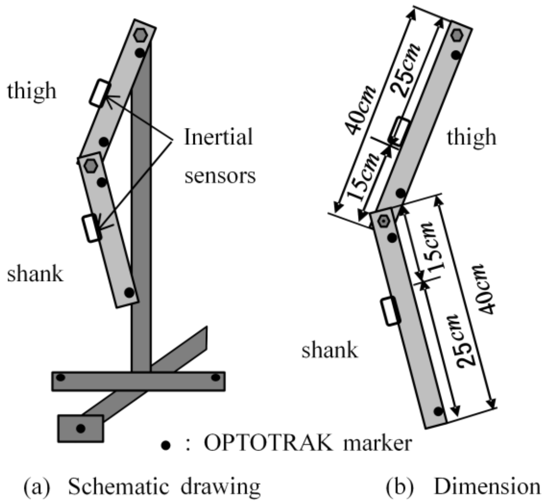


Fig. 2. A rigid body model used in the experiment.

First, thigh and shank inclination angles under the static condition (posture) were measured for 15*s* at 9 target angles of 0*deg*, ±30, ±60, ±90, and ±120*deg*. Zero degree means the direction of gravitational force. Five trials were conducted for each target angle. Second, the inclination angles and joint angle were measured under the dynamic condition (movement) for 35*s* with 5 target angle ranges of ±15, ±30, ±45, ±60, and ±75*deg*. The thigh was moved for the angle range with the cycle period of 2*s*, while the shank was moved freely associated with movement of the thigh. The movement velocity of the thigh was determined based on our previous measurements with neurologically intact subjects [8], in which average angular velocities of the thigh during fast walking were between 80*deg/s* and 130*deg/s*. In the measurement of this paper, average movement velocities of the thigh were set at 30 to 150*deg/s* based on the results. Five trials were conducted for each target angle range.

Acceleration and angular velocity signals of each sensor were measured with the sampling frequency of 100*Hz*. Accelerometer outputs were filtered with low-pass filter with cut off frequency of 20*Hz*. From the results of preliminary experiments, the parameter value of the Kalman filter under the static and dynamic conditions were determined to 10^5

and 10^7, respectively. For evaluating the accuracy in angle measurement of the sensors, root mean squared error (RMSE) and correlation coefficient between measured angles and reference values were calculated. Measurement timing of reference and sensor signals were synchronized at the first peak of the inclination angles of the thigh.

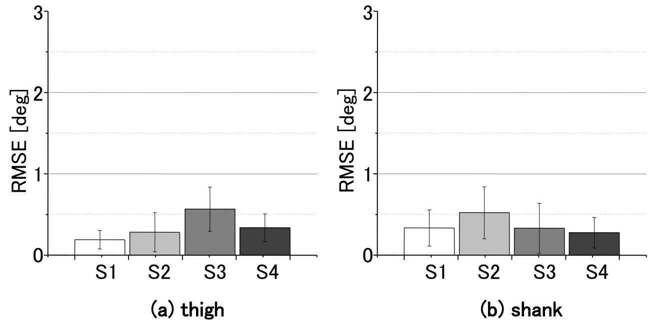
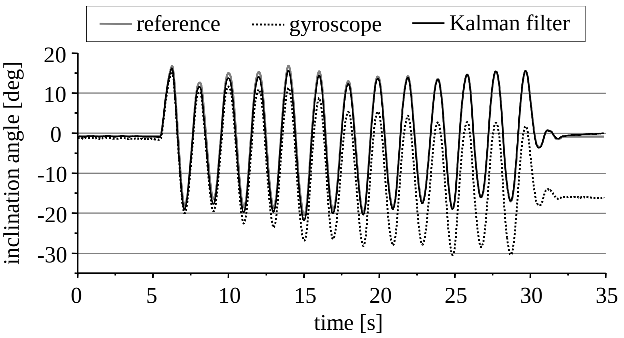
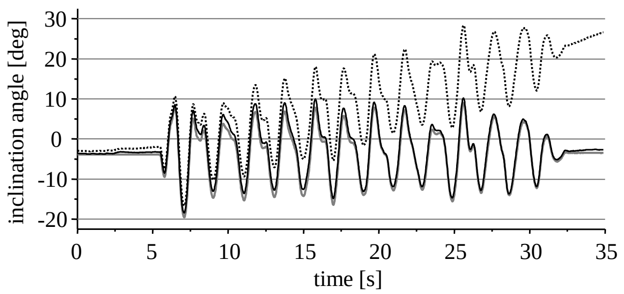


Fig. 3. Evaluation results of angle measurement under the static condition.



(a) thigh inclination angle



(b) shank inclination angle

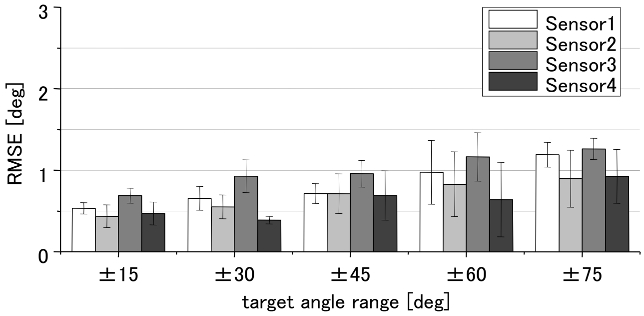
Fig. 4. An example of angle measurement results under the dynamic condition. (Sensor1, ±15deg).

IV. Results

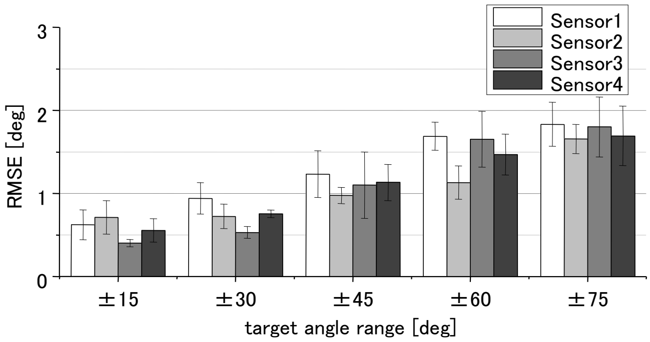
Fig. 3 shows RMSE of inclination angles under the static condition. All sensors showed small RMSE values, which were less than 0.56*deg* on average of all trials. Differences of the RMSE between the shank and the thigh angles are considered to arise from differences in the sensor used.

Fig. 4 shows an example of measured inclination angles under the dynamic condition. As seen in Fig. 4, the shank segment was moved irregularly according to the cyclic movement of the thigh. It is also shown that the error of angles calculated from gyroscope only was corrected by the Kalman filter, and the corrected angles became almost equal with their reference signals.

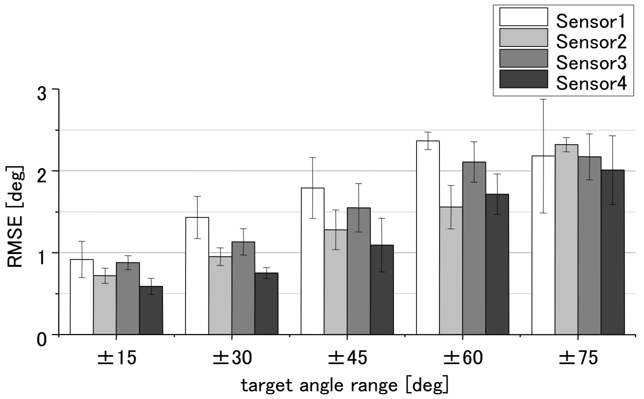
Fig. 5 shows RMSE of inclination and joint angles under the dynamic condition. Average values of five trials for each target angle range were less than 1.26*deg*, 1.83*deg*, and 2.37*deg* for the thigh and the shank inclination angles and joint angle, respectively. The RMSE values of the shank inclination angle were larger than those of the thigh. The average values of the correlation coefficients of the inclination angles were larger than 0.996 for all target angle ranges with all of sensors, while those of joint angles were larger than 0.980.



(a) thigh



(b) shank



(c) knee

Fig. 5. Evaluation results of angle measurement under the dynamic condition.

V. Discussions

As expected, there was no large difference in measurement accuracy between different type of sensors. It is suggested from comparison between wireless sensors (Sensor 1, 3 and 4) that the difference in measurement resolution has small influence on measurement accuracy. This means that inertial sensors can be replaced with inexpensive or latest sensors, if the measurement resolution is higher than or similar to those of the sensors used in this paper.

Wireless communication has difficulty in synchronizing the measurement timing, and is affected by the communication environment. Actually in case of using the wireless sensors, there were differences of 10 to 20 *ms* in the measurement timing in some trials between sensors on the thigh and the shank. The RMSE values of the knee joint angle are generally increased by the difference of the measurement timing between 2 sensors. However, differences of RMSE of the knee joint angle were small between Sensor 2 (wired) and Senor 3 (wireless), even though sensitivities of accelerometer and gyroscope in Sensor 3 (wireless) are lower than Sensor 2 (wired). Therefore, it is suggested that the differences of 10 to 20 *ms* in the measurement timing do not cause significant error in measurement and that difference in communication systems (wireless or wired) has small influence on measurement.

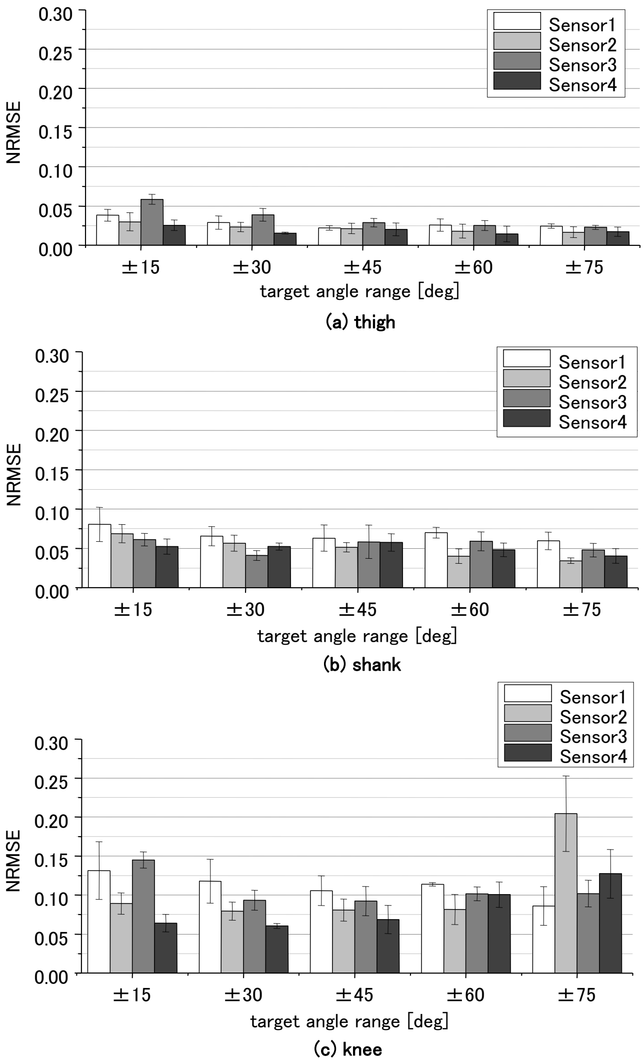


Fig. 6. Results of RMSE normalized by the standard deviation of the reference signal.

As shown in Fig. 5, RMSE of the measured angles under the dynamic condition showed a tendency of increasing error as target angle range increased. Here, normalized RMSE (NRMSE), which is RMSE normalized by the standard deviation of the reference signal, is shown in Fig. 6. Four sensors showed almost same NRMSE values for all the target angle range. However, NRMSE values of the shank angle were still larger than the errors of the thigh angle. This suggests that larger movement range of the shank than that of the thigh is not the only cause of increased RMSE of the shank. Possible other reason of increasing the error is movement acceleration. The error of the angle calculated from the acceleration sensor is increased by the movement acceleration involved in the output of the accelerometer. Fig. 7 shows average values of movement acceleration calculated from outputs of Sensor 1. The values were calculated by subtracting gravitational acceleration from the magnitude of acceleration vector. For all the target angles, average values of movement acceleration of the shank angle are larger than those of thigh angle. In addition, as the target angle range increased, the average movement acceleration increased. From these results, the movement acceleration is considered to be the cause of the error increase as target angle range increases.

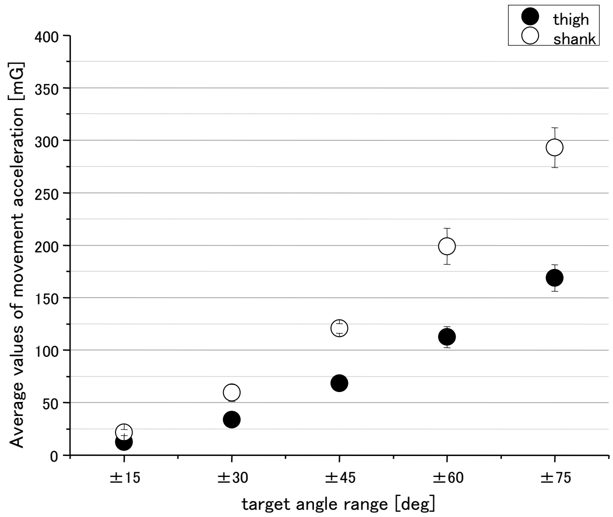


Fig. 7. Average values of movement acceleration calculated from outputs of Sensor 1.

In this paper, parameter value to determine the gain of the Kalman filter was fixed for all sensors (10^5 under the static condition, and 10^7 under the dynamic condition) in analyzing the measurement data. Basically, it is better to correct measured angles with gyroscope more strongly by acceleration signal under the static condition than those under the dynamic condition in the Kalman filtering based method. Although it was found that the Kalman filtering based method could measure angles stably with almost same accuracy for all of sensors, there is a possibility of a further improvement of measurement accuracy by adjusting parameter value of the Kalman filter according to the magnitude of the movement acceleration and that of the offset drift of gyroscopes.

VI. Conclusion

In this paper, developed wired and wireless sensors were tested in angle measurement comparing to 2 commercially available sensors. It was shown that the Kalman filtering based angle measurement method could measure inclination angles and joint angles with stable, good accuracy with all of sensors. It was suggested that the difference in communication systems and difference in measurement resolution has small influence on measurement accuracy. It would be possible to replace inertial sensors with newly developed inertial sensors, inexpensive one, or latest commercially available one.

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