# A Preliminary Study on Evaluation of Circumduction Movement during Gait with Wireless Inertial Sensors

Maho Shiotani, *Student Member, IEEE*, Takashi Watanabe, *IEEE Member*

*Abstract*— **Recently, inertial sensors have been used to measure human movements for the purpose of rehabilitation. In evaluation of motor function for rehabilitation, reference data measured from healthy subjects with inertial sensors is needed. In addition, since lower limbs perform 3-dimensional movements during gait, it is needed to analyze 3-dimensional gait movements. The plot of 3-dimensional vector locus can be useful to understand 3-dimensional movements. The purposes of this paper were to show usefulness of the vector locus in understanding circumduction during gait, and to test an evaluation parameter for 3-dimensional movements during walking as reference data. Gait of 12 healthy subjects were measured, and then vector loci were plotted in the 3-dimensional space. Shape of the vector locus was evaluated by the width of each component as one of the reference data. It was suggested that the vector loci plotted in 3-dimensioinal space or those projected on horizontal plane were useful to understand circumduction during gait. It was also suggested that the width of vector locus was useful to evaluate differences of movement between subjects.**

## I. INTRODUCTION

Evaluating the motor function is important in rehabilitation for impaired motor function of patients. Commonly, physical therapists evaluate a level of motor function from visual information, manually measured angles, or measurement of time in 10 *m* walking test. Those evaluations can be practical because of easiness in using at clinical site. However, since it may depend on experience of therapists, it is needed to develop objective and quantitative evaluation method for clinical use. Objective and quantitative evaluation makes it possible to feedback objective data to patients, and then it is expected to increase rehabilitation effect.

The optical 3-dimensional motion analysis system has been used commonly in research work to measure movements. Although this system can be effective to evaluate human movement objectively and quantitatively, there are some shortcomings that the measurement condition is limited in place and space, and costs of these systems are very high. Therefore, it is difficult to use the system for rehabilitation at clinical site. On the other hand, in recent years, inertial sensors such as accelerometers and gyroscopes have been actively used to measure and analyze human movements as substitute for the optical 3-dimensional motion analysis system. These sensors are small, easy to setting, and low cost, thus it is useful to measure movements at clinical site.

In order to evaluate motor function using inertial sensors, reference data measured from healthy subjects with inertial sensors can be useful. Although there are many researches on measuring movement of motor disabled patients [1-4], there are few studies trying to make reference data by measuring gait movements of many healthy subjects with inertial sensors in order to compare with patient's gait movement to use in rehabilitation programs. Therefore, in our research group, for the purpose of making reference data including new evaluation parameters, gait movements of healthy subjects were measured with inertial sensors [5].

In order to make reference data, it is needed to analyze 3-dimensional gait movements, since lower limbs perform 3-dimensional movements during gait. In our previous study, a measurement method of angles in the sagittal and the frontal planes was developed, which was shown to have reasonable measurement accuracy in measurement of angles of rigid body model [6]. Using this method, it was suggested that foot inclination angles in the sagittal, the frontal and the horizontal planes during walking can be measured with an inertial sensor [7]. Although measurement of joint angle or segment tilt angle in the sagittal or the frontal plane is useful to evaluate joint movement during gait, it may be difficult to understand integrated movements of those joint movements. Since large circumduction of lower limb during gait is a characteristic change in hemiplegic gait, it is useful to analyze the circumduction during gait for evaluation of gait function. In order to understand 3-dimensional movements of lower limb during walking and evaluate the circumduction, changes of knee joint position in 3-dimensional space is considered to be useful. Three dimensional locus of the vector that is set to the thigh is considered to provide similar information to the knee joint position. The quaternion-based method used to calculate angles in the previous study [6] can also calculate such segment vector locus.

The first purpose of this paper was to show usefulness of the vector locus in understanding circumduction during gait. The second purpose was to test an evaluation parameter for 3-dimensional movements during walking as reference data. Gait of 12 healthy subjects in their twenties were measured, and then vector loci were plotted in the 3-dimensional space. Shape of the vector locus was evaluated by the width of each component as one of the reference data.

## II. MEATHODS

### A. Measurement Method

In our previous study, the wearable motion measurement system was developed [8]. The system consisted of seven wireless inertial sensors (WAA-010, Wireless Technologies) and a PC (Fig.1). A 3-axis accelerometer (ADXL345, Analog Devices) and a 3-axis gyroscope (IDG-3200, InvenSense)

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M.Shiotani and T.Watanabe are with the Graduate School of Biomedical Engineering, Tohoku University, Sendai, Japan (e-mail: {maho.shiotani, nabet} @bme.tohoku.ac.jp).

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were contained in each inertial sensor. These sensors were fixed on lower limb segments, that is, the feet, the shanks and the thighs of both legs, and the lumbar region. Each sensor was put inside of a pocket of stretching band and fixed to each segment. Acceleration and angular velocity signals were measured with each sensor using a sampling frequency of 100 Hz, and send to PC via Bluetooth network and recorded. Measurement and recording were implemented in LabVIEW (National Instruments).

Measurements were conducted with 12 healthy subjects (6 males and 6 females, 21-23 years old) using the inertial sensor system. Subjects were asked to walk 15 *m* on level floor at normal walking speed (usual comfortable speed chosen by subjects). Six trials were performed with each subject.

### *B. Data Analysis*

In order to evaluate steady state walking, the first two and the last two strides in each trial were removed from analysis. The first two trials were also removed as rehearsals. Low Pass Filter was applied to acceleration signals with a cut off frequency of 1.0 Hz in order to remove high frequency noises. In this paper, the sensors fixed on both thighs were used to analyze gait movements.

The 3-dimentional angle measurement method developed in our previous study can calculate both segment tilt angle and vector locus in 3-dimensional space. At first, 3-dimensional unit vectors were set to both thigh segments, which were $\boldsymbol{e}_{Tl}$ for the left thigh and $\boldsymbol{e}_{Tr}$ for the right thigh as shown in Fig. 2. The global coordinate system was defined as shown in Fig.2, in which *x, y* and *z* axes were defined as the traverse direction, the vertical direction, and the travelling direction, respectively. Block diagram of calculation method of the angle and the vector locus is shown in Fig.3. As shown in Fig. 3, using the triaxial angular velocity $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)$ and acceleration $\boldsymbol{a} = (a_x, a_y, a_z)$, quaternion $\boldsymbol{q}$ and $\boldsymbol{z}$ are calculated by followings.

$$\boldsymbol{q}_{k+1} = \frac{1}{2}\begin{bmatrix} 2 & -\Delta t\omega_{xk} & -\Delta t\omega_{yk} & -\Delta t\omega_{zk} \\ \Delta t\omega_{xk} & 2 & \Delta t\omega_{zk} & -\Delta t\omega_{yk} \\ \Delta t\omega_{yk} & -\Delta t\omega_{zk} & 2 & \Delta t\omega_{xk} \\ \Delta t\omega_{zk} & \Delta t\omega_{yk} & -\Delta t\omega_{xk} & 2 \end{bmatrix}\boldsymbol{q}_k \tag{1}$$

$$\boldsymbol{z}_k = \left[\cos\left(\frac{\theta_k}{2}\right), \sin\left(\frac{\theta_k}{2}\right) \times \left[\frac{\boldsymbol{A}_k}{\left\|\boldsymbol{A}_k\right\|}\right]\right] \tag{2}$$

$$\theta_k = \cos^{-1}\left(\boldsymbol{a}_k \cdot \boldsymbol{a}_0\right) \tag{3}$$

$$\boldsymbol{A}_k = \boldsymbol{a}_k \times \boldsymbol{a}_0 \tag{4}$$

Where $\boldsymbol{a}_k$ and $\boldsymbol{a}_0$ mean the gravitational acceleration at time *k* and that at the initial position, respectively. Since integration error were accumulated in $\boldsymbol{q}$, Kalman filter was used to correct the integration error by using $\boldsymbol{z}$ as the observation value. That is, prediction and correction in Kalman filtering were represented by Eqs. (1) and (5).

$$\hat{\boldsymbol{q}}_k = \hat{\boldsymbol{q}}_k^- + \boldsymbol{K}(\boldsymbol{z}_k - \hat{\boldsymbol{q}}_k^-) \tag{5}$$

Then, rotation matrixes $\boldsymbol{R}$ were calculated from the corrected quartanion $\hat{\boldsymbol{q}}$ by Eq. (6). In Eq. (6), $q_0, q_1, q_2, q_3$ mean components of quartanion $\hat{\boldsymbol{q}}$.

$$\boldsymbol{R} = \begin{bmatrix} 2q_0^2 - 1 + 2q_1^2 & 2q_1q_2 + 2q_0q_3 & 2q_1q_3 - 2q_0q_2 \\ 2q_1q_2 - 2q_0q_3 & 2q_0^2 - 1 + 2q_2^2 & 2q_3q_2 + 2q_0q_1 \\ 2q_1q_3 + 2q_0q_2 & 2q_3q_2 - 2q_0q_1 & 2q_0^2 - 1 + 2q_3^2 \end{bmatrix} \tag{6}$$

Using the rotation matrixes, segment vectors were rotated. After that, vectors were calibrated by using vectors measured at the standing position before walking of the 1st analyzed trial of each subject as the vertical direction. Measured walking data were divided into each stride by detecting the heel contact (HC). The HC was detected by threshold of acceleration signal measured with the sensor attached on the shank [9]. Then,

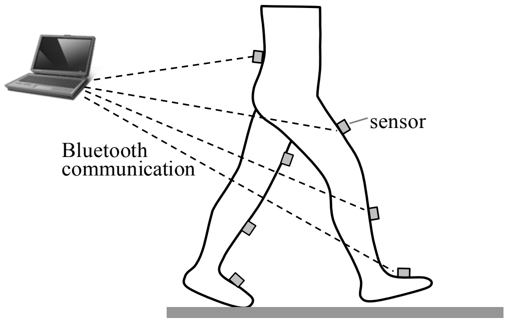


Figure 1. Outline of the wearable sensor system used in this study.

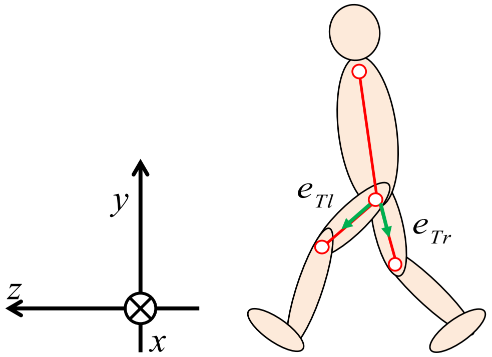


Figure 2. Definition of the global coordinate system and segment vectors.

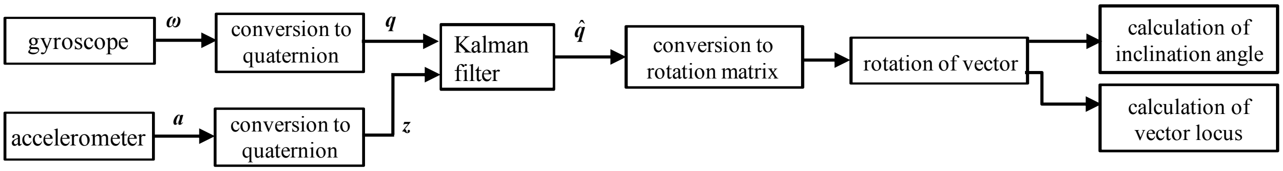


Figure 3. Block diagram of calculating method of inclination angle and vector locus of 3D movements from measured acceleration and angular velocity signals.

time of each gait cycle was normalized to 100%. Finally, *x, y,* and *z* components of the thigh segment vector at each time were plotted in the 3-dimensional space as a vector locus of the thigh segment. Therefore, vector locus of the thigh segment shows 3-dimensional movement of the thigh segment. In this study, vector loci of the right thigh were calculated to show usefulness in understanding circumduction during gait as a preliminary test.

## III. MEASUREMENT RESULTS

Examples of vector loci for continuous three strides measured from one subject are shown in Fig. 4. The vector loci show the 3-dimensional movements of the right thigh segment. These are related to movements of right knee position. There were little differences of vector locus between different strides.

On the other hand, vector loci measured from different subjects showed different patterns (Fig. 5). In order to show the difference clearly, vector loci were projected to the sagittal, the frontal, and the horizontal planes (Fig. 6). The vector loci projected to the zy plane that means the sagittal plane showed almost same patterns between subjects. On the other hand, the vector loci in the xy and the xz planes that mean the frontal and the horizontal planes show different patterns between subjects.

In order to evaluate the shape of the vector locus, width of each component of the locus was calculated (Fig. 7). The width was calculated as the difference between the maximum value and the minimum value of each component. There were no significant differences in the width between male and female. The variation coefficient for the width of *x* component was 0.323, that of *y* component was 0.209, and that of z component was 0.105. The variation coefficient for the width of *x* component was larger than other components.

## IV. DISCUSSION

The vector loci shown in Figs. 4 and 5 are related to knee position during walking. It is easily found that the knee was located in front of the body at the heel contact, and then went

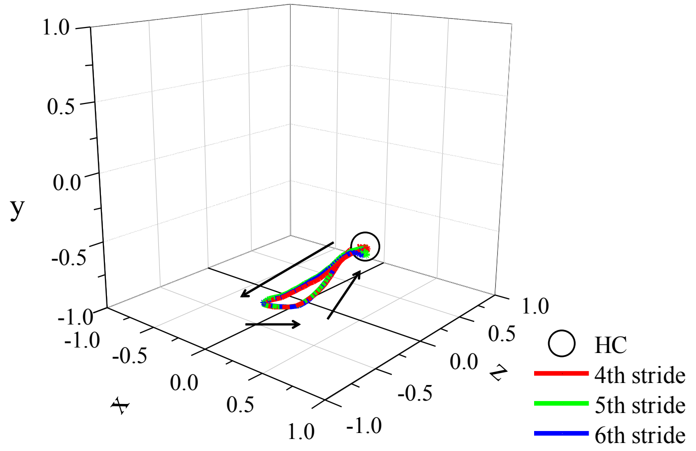


Figure 4. Vector loci of the thigh segment of three strides from one subject. (*The arrow shows movement direction. The open circle shows the heel contact (HC) point of the 4th stride.)*

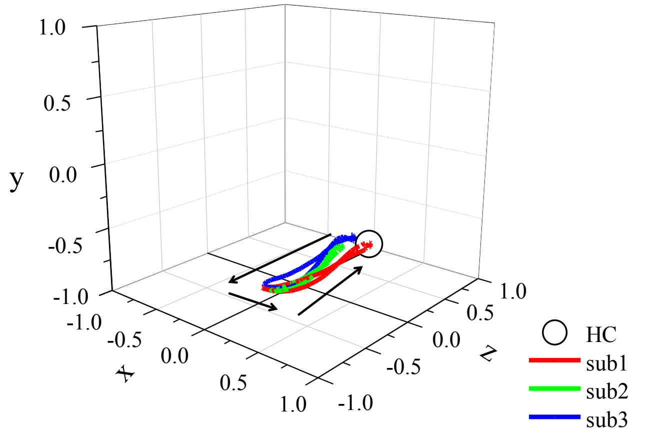
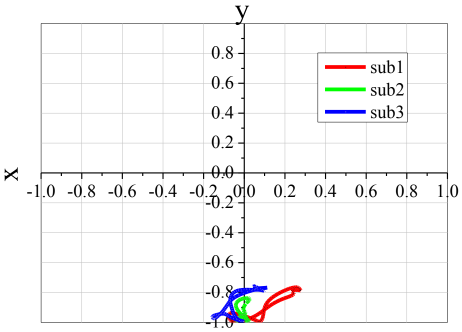
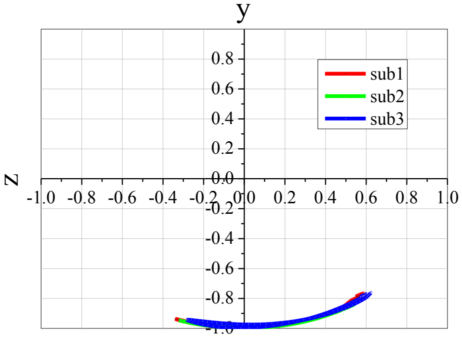


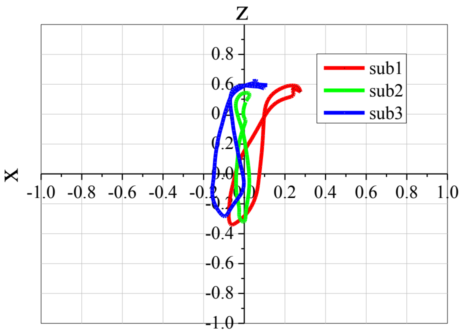
Figure 5. Vector loci of three different subjects.(*The arrow shows direction of vector movement. The open circle shows the heel contact point of sub1.*)



(a) vector loci projected to the xy plane



(b) vector loci projected to the zy plane



(c) vector loci projected to the xz plane

Figure 6. The projected vector loci of three different subjects. (*xy -plane means the frontal plane, yz-plane means the sagittal plane, and zx-plane means the horizontal plane. )*

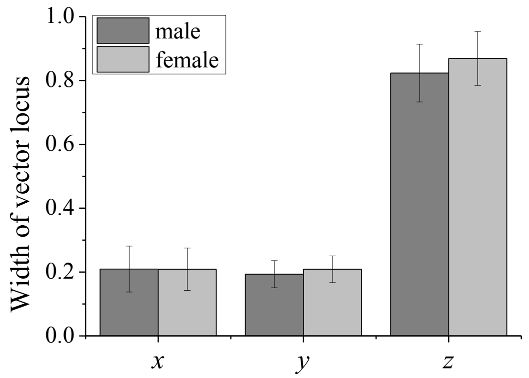


Figure 7. The width of *x, y,* and *z* components of vector locus.

backward and returned in front of the body again at the next heel contact. The circumduction during gait can be found clearly in Fig. 6 (c). It is suggested that the segment vector loci plotted in 3-dimensional space or the loci projected on the horizontal plane can be useful to understand circumduction during walking. It is expected to increase rehabilitation effect by understanding inadequate circumduction of patient's gait movement objectively and feedbacking calculated data.

In Figs. 5 and 6, differences and parallel shifts of the vector loci between three subjects are found. The differences of the width seen in the xz-plane in Fig. 6 (c) are considered to be a difference of movement. However, the shifts are considered to include the differences in calibration between subjects. In the analysis of this paper, the segment vectors were calibrated to the vertical direction by the measured data at the standing position before walking of the 1st analyzed trial of each subject. Thus, it is needed to study on the adequate method to calibrate the segment vector.

In this paper, in order to remove the influence of the difference in the calibration process, the width of each component of vector locus was calculated. The width of *x, y*, and *z* components shown in Fig. 7, did not show significant difference between male and female ($p>0.10$). In previous studies, it was suggested that hip joint flexion, adduction, and internal rotation of gait movement of female was significantly greater than those of male [10, 11]. Since movements of the thigh segment vector have relationship to hip joint angle, the result of this paper may be different from that of the previous studies. Since the number of subject of this paper was smaller than those of the previous studies, it is needed to measure gait movement with more healthy subjects.

The width of vector locus can be one of the reference data to evaluate difference from normal gait. However, the width of *x* component has larger variation than those of *y* or *z* components. The width of *x* component reflects movements in the traverse direction. Thus the large variation is considered to be caused by differences of movement at traverse direction between subjects. For example, some subjects who showed the large width of *x* component might walk like runway model, and some subjects who showed small width of *x* component might move their legs mainly in the sagittal plane. Therefore, it is considered that the width of vector locus can be useful to evaluate differences of movement between subjects. In addition, in measurement of patient's gait movement, if some patients show much larger width of *x* component than that of healthy subjects, it suggests that the patients walk with large circumduction.

Quaternion-based method used in this paper could measure inclination angles of rigid body model with reasonable measurement accuracy [6]. This suggests that vector movement can be measured with reasonable accuracy, since inclination angles are calculated from vector components. However, in measurements with the rigid body model, sensors were set almost ideally. On the other hand, in measurements of human movement, the sensor might be set on the body with a tilt, which increases measurement error. Therefore variation of *x* component might be affected by the measurement error. It is better to evaluate measurement accuracy of vector movement with measurements of human movement.

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