

Human Motion Estimation Using Only Inertial Sensors

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ABSTRACT

When human motion is estimated using inertial sensors, measurement over long periods of time results in the accumulation of errors in yaw angle direction. There is a method of compensating for this using magnetometers, but this method is not effective in environments where the magnetism is unstable. A method of compensating for errors in yaw angle direction without using magnetometers was therefore investigated. A method was devised in which the measurement object is defined as motion in which every link of the body has the same yaw angle when averaged over time. Compensation is then applied by reducing the differences in yaw angle between the links. When estimating walking motion, the difference in joint angle estimated by the method using inertial sensors and magnetometers and that estimated by optical motion capture has a root mean square of 8.4 deg, while the corresponding figure with the present method using only inertial sensors is 8.9 deg. This indicates equal levels of accuracy. It was also confirmed that the integral calculation error in yaw angle when measuring walking motion over a long period of time was equally reduced.

1. Introduction

Making correct measurements of human motion is the first step toward a variety of biomechanics analyses⁽¹⁾. If it were possible to obtain a quantitative grasp of bodily motion, then it would be possible to examine appropriate methods of guidance, and evaluate their effectiveness, in the areas of rehabilitation⁽²⁾ and sports training⁽³⁾. This could also be applied to the prediction of risks of injury and disorders resulting from body burden on athletes and laborers engaging in heavy work⁽⁴⁾. In recent years, wearable robots that assist with human movement have been used to reduce body burden as well as in rehabilitation. Since human motion is the basis for control of assistive force⁽⁵⁾, motion estimation is a key functionality for a wearable robot.

Optical motion capture is one of the previously existing methods of motion measurement and it is widely used⁽¹⁾. This method involves attaching reflective markers to the body and capturing images with multiple infrared cameras to calculate three-dimensional positions and then estimate the body orientation. This method enables measurement of position with a high degree of accuracy, but it requires

surrounding the measurement object with multiple cameras, which limits the range of possible measurement. Sometimes the presence of an obstruction between the camera and the measurement object may also make it a challenge to identify the positions of reflective markers. A method has been used in recent years to estimate joint position using machine learning with RGB images captured with ordinary cameras⁽⁶⁾. Since this requires images to be captured externally, however, it has limitations similar to those of optical motion capture.

As a method that does not have the above limitations, there is the use of a compact inertial sensor that can be attached to the body. This method uses this inertial measurement unit (IMU) to estimate three-dimensional orientation⁽⁷⁾. An IMU can measure acceleration and angular velocity, and numerical integration of angular velocity enables estimation of orientation. By comparison with the optical motion capture method and the machine learning-based method that estimates the skeletal frame from imagery, the method here involves less computation and it allows processing at high speed with lower-cost processors. There are issues, however, in that angular velocity measurement errors and numerical integration

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errors accumulate, and the estimated orientation and actual orientation end up diverging over time. In order to address these issues, methods have been proposed that use the direction of gravity estimated from the measured acceleration as a guide in determining compensation for orientation in the roll and pitch directions^{(8), (9)}. In order to further determine compensation for orientation in the yaw direction, methods have been proposed for estimating orientation by means of a magnetic, angular rate, and gravity (MARG) sensor incorporating a magnetometer^{(10), (11)}. However, yaw angle compensation using geomagnetism is only effective in an environment where stable measurement of geomagnetism is possible. Magnetic fields are greatly changed in the vicinity of the steel frames of buildings, metallic fixtures and furniture, and other such magnetic bodies, and this frequently makes it so geomagnetism cannot be measured correctly. When measuring the motion of a human body equipped with a wearable robot, this can also mean that the accuracy of geomagnetism measurement ends up being reduced by the influence of the metallic frame and motor of the device.

As indicated by the above, although the estimation of orientation using the IMU is not affected by the camera's angle of view or obstructions, there are issues with yaw angle compensation that uses geomagnetism as a guide. For the present research, therefore, a method of compensation for yaw angle was examined that does not rely on magnetometers but instead imposes restrictions on the motion of the measurement object and uses those restrictions to determine the compensation. First, the body was divided into segments with boundaries at the joints and the human body was considered as a rigid link system. When the measurement object is limited to motion in which the yaw angle of each link ends up in the same direction when averaged over time, the relationships between the orientations of every link can be used as a guide for determining yaw angle compensation. A method of compensation for the yaw angle in body coordinates determined solely from the IMU was successfully devised based on this conceptual approach, and that method is therefore reported here.

2. Method for Estimating Body Orientation

2.1. Sensor Placement and the Body Model

In order to estimate motion with the IMU, the human body is first modeled as a rigid link system. Figure 1 shows an example of a body with the torso, pelvis, left and right thighs, lower legs, and feet each modeled as rigid links. The links are joined by joints that have three orthogonal rotation axes in each space between the links. An IMU is attached to each link, and the system of coordinates of the IMU and of the link are considered to be coincident. In other words, if the orientation of the IMU is estimated, then the orientation and joint angle of the link will become clear. Every link is allocated a unique number, i , and in the example of Fig. 1,

$i \in \{0, 1, 2, \dots, 6, 7\}$. Link 0 is the link that will serve as a reference for calculation of the yaw angle compensation amount, which will be explained later, and it will be referred to as the base link.

As shown in Fig. 2, each IMU has its own sensor coordinate system. The acceleration and angular velocity obtained from an IMU are as observed in that sensor coordinate system. Here the acceleration in the X, Y, and Z directions in the sensor coordinate system observed using the IMU for Link i are designated $a_{i,x}$, $a_{i,y}$, $a_{i,z}$, respectively. Similarly, the angular velocity around the X, Y, and Z axes in the sensor coordinate system are designated $\omega_{i,x}$, $\omega_{i,y}$, and $\omega_{i,z}$, respectively.

2.2. Representation of Three-dimensional Orientation

Orientation is commonly represented using an Euler angle, which is made up of three-dimensional elements, and a unit quaternion, which is made up of four-dimensional elements. An Euler angle can represent orientation with a small number of elements, but there is an orientation (singularity) that becomes numerically unstable and cannot be represented. In the present research, therefore, orientation is represented using the unit quaternion, which does not have a singularity.

The rotation from coordinate system A to coordinate

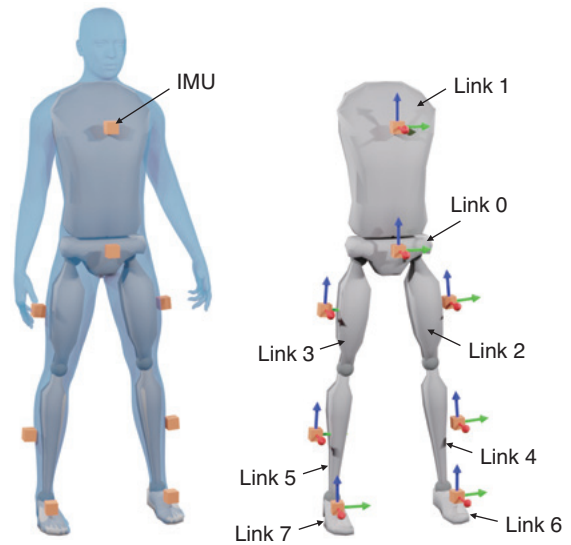


Fig. 1 Articulated human body and IMU allocation

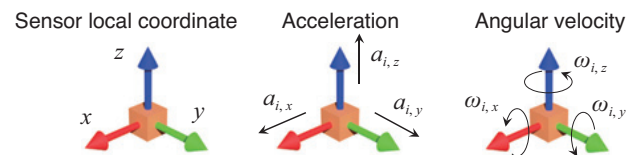


Fig. 2 Sensor coordinate systems

system B is expressed as shown in Eq. (1) by the unit quaternion ${}^A_B\hat{e}$. Here, coordinate system B is taken to rotate only by θ with respect to the normalized rotation axis $r = [r_x \ r_y \ r_z]$ of coordinate system A. Orientation will be a normalized unit quaternion as in Eq. (2).

$$\begin{aligned} {}^A_B\hat{e} &= [e_1 \ e_2 \ e_3 \ e_4] \\ &= [\cos \frac{\theta}{2} \ -r_x \sin \frac{\theta}{2} \ -r_y \sin \frac{\theta}{2} \ -r_z \sin \frac{\theta}{2}] \end{aligned} \quad (1)$$

$$\hat{e} = \frac{e}{\|e\|} \quad (2)$$

As shown in Eq. (3), a quaternion product $\otimes$ can also be used to translate vector ${}^A_V$ in coordinate system A to ${}^B_V$ represented in coordinate system B^{(10), (11)}.

$${}^B_V = {}^A_B\hat{e} \otimes {}^A_V \otimes {}^A_B\hat{e}^* \quad (3)$$

However, ${}^A_B\hat{e}^*$ is a conjugation of ${}^A_B\hat{e}$, and is defined as shown in Eq. (4).

$${}^A_B\hat{e}^* = [e_1 \ -e_2 \ -e_3 \ -e_4] \quad (4)$$

2.3. Roll and Pitch Angle Compensation

The orientation error that is obtained by integrating the angular velocity measured by means of the IMU can be compensated for by taking the direction of gravity estimated from acceleration as a guide. Madgwick, et al.⁽¹¹⁾ proposed a method that takes this as an optimization problem that minimizes the roll and pitch angle error and determines the compensation direction from the gradient of the objective function. For the present research, a similar method of roll and pitch angle compensation has been adopted. First, the difference between the direction of gravity calculated from the estimated orientation of Link i and the measured acceleration is represented by the function f_g , which is defined as follows.

$$f_g({}^S\hat{e}_i, {}^S\hat{a}_i) = {}^S\hat{e}_i^* \otimes {}^G\hat{d}_g \otimes {}^S\hat{e}_i - {}^S\hat{a}_i \quad (5)$$

$${}^G\hat{d}_g = [0 \ 0 \ 0 \ 1] \quad (6)$$

$${}^S\hat{a}_i = [0 \ a_{i,x} \ a_{i,y} \ a_{i,z}] \quad (7)$$

${}^G\hat{d}_g$ is the direction of gravity in an absolute coordinate system while ${}^S\hat{a}_i$ is the acceleration vector measured by means of the IMU. The optimization problem that, using Eq. (5), takes the orientation ${}^S\hat{e}_i$ of Link i as an objective variable is defined as in Eq. (8). This is the least-squares problem that determines the orientation ${}^S\hat{e}_i$ where the measured acceleration and the direction of gravity coincide. The gradient of the objective function in Eq. (8) is defined as in Eq. (9). However, J_g is the Jacobian matrix of f_g .

$$\min_{{}^S\hat{e}_i} \frac{1}{2} \|f_g({}^S\hat{e}_i, {}^S\hat{a}_i)\|^2 \quad (8)$$

$$\begin{aligned} \text{grad}_g({}^S\hat{e}_i, {}^S\hat{a}_i) &= \nabla \left\{ \frac{1}{2} \|f_g({}^S\hat{e}_i, {}^S\hat{a}_i)\|^2 \right\} \\ &= J_g^T({}^S\hat{e}_i) f_g({}^S\hat{e}_i, {}^S\hat{a}_i) \end{aligned} \quad (9)$$

From the gradient in Eq. (9), the angular velocity can be compensated⁽¹¹⁾ as shown below. Here the angular velocity of Link i at time t is ${}^S\dot{e}_{i,t}$ and the acceleration is ${}^S\hat{a}_{i,t}$.

$${}^S\dot{e}_{i,t} \leftarrow {}^S\dot{e}_{i,t} - \beta_g \frac{\text{grad}_g({}^S\hat{e}_{i,t}, {}^S\hat{a}_{i,t})}{\|\text{grad}_g({}^S\hat{e}_{i,t}, {}^S\hat{a}_{i,t})\|} \quad (10)$$

2.4. Objective Function of Yaw Angle Compensation

The objective function of yaw angle compensation is defined by making use of the fact that the measurement object is a motion for which the direction of each link (yaw angle direction) is identical when averaged over time. First, the vector ${}^G\hat{v}_i$ that indicates the yaw angle direction of Link i is defined. ${}^G\hat{v}_i$ is calculated according to Eq. (12) and is a vector that is orthogonal to each unit vector ${}^S\hat{n}_i = [0 \ 0 \ 1 \ 0]$ in the Y axis direction of Link i , and unit vector ${}^G\hat{d}_g$ in the Z axis direction of the global coordinate system. As shown in Fig. 3, ${}^G\hat{v}_i$ is a unit vector on the X-Y plane (horizontal plane).

$${}^G\hat{v}_i = ({}^S\hat{e}_i \otimes {}^S\hat{n}_i \otimes {}^S\hat{e}_i^*) \times {}^G\hat{d}_g \quad (11)$$

$${}^G\hat{v}_i = \frac{{}^G\hat{v}_i}{\|{}^G\hat{v}_i\|} \quad (12)$$

Next, as was done with the roll and pitch angles, the compensation direction is derived by means of gradient descent. Using ${}^G\hat{v}_i$ and the Y axis direction ${}^S\hat{n}_i$ in the base link coordinate system, the objective function for yaw angle compensation is defined as in Eq. (13). This objective function is defined for links other than the base link ($i \neq 0$).

$$f_{yaw}({}^S\hat{e}_i) = ({}^S\hat{e}_i \otimes {}^S\hat{n}_i \otimes {}^S\hat{e}_i^*) \cdot {}^G\hat{v}_i \quad (13)$$

The objective function f_{yaw} is a scalar value. As shown in Fig. 4, $|f_{yaw}|$ is zero when the X-Z plane (sagittal plane) as viewed in the local coordinate system for Link 0 is parallel with yaw angle direction vector ${}^G\hat{v}_i$ for Link i and it is one when they are orthogonal. This is an indicator of the extent to which the yaw angle direction of Link i and the yaw angle direction of the base link coincide.

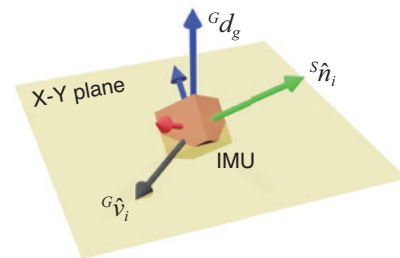


Fig. 3 Yaw angle direction of Link i

2.5. Yaw Angle Compensation

The objective function in Eq. (13) is defined from the orientations of two links, Link $i \neq 0$ and the base link where $i = 0$. When considering yaw angle compensation for the whole body's links, every link other than the base link influences and is influenced by the other links through the base link. Consequently, the yaw direction compensation amount has to be calculated with all the links taken into consideration. Consider unifying the objective functions for yaw angle compensation for all the links and calculating the compensation amount from the gradient. As in the next equation, the orientation of all the links is combined and expressed as orientation Q .

$$Q = [\begin{smallmatrix} {}^S\hat{e}_0 & {}^S\hat{e}_1 & {}^S\hat{e}_2 & \cdots & {}^S\hat{e}_{N-2} & {}^S\hat{e}_{N-1} \end{smallmatrix}] \in \mathbb{R}^{4N} \quad (14)$$

When determining the yaw angle compensation amount for the whole body, the objective function is defined as follows.

$$\min_Q \frac{1}{2} \|F_{yaw}(Q)\|^2 \quad (15)$$

$$F_{yaw}(Q) = \begin{bmatrix} f_{yaw}({}^S\hat{e}_1) \\ f_{yaw}({}^S\hat{e}_2) \\ \vdots \\ f_{yaw}({}^S\hat{e}_{N-2}) \\ f_{yaw}({}^S\hat{e}_{N-1}) \end{bmatrix} \in \mathbb{R}^{N-1} \quad (16)$$

F_{yaw} is an N -dimensional vector and it expresses the extent to which the sagittal plane of the base link and the yaw angle direction ${}^G\hat{v}_i$ of each link are orthogonal. When the yaw angle directions ${}^G\hat{v}_i$ of all the links become parallel with the sagittal plane of the base link, F_{yaw} becomes a vector in which all the elements are zero. As in Eq. (9), the gradient of F_{yaw} can be calculated as follows using the

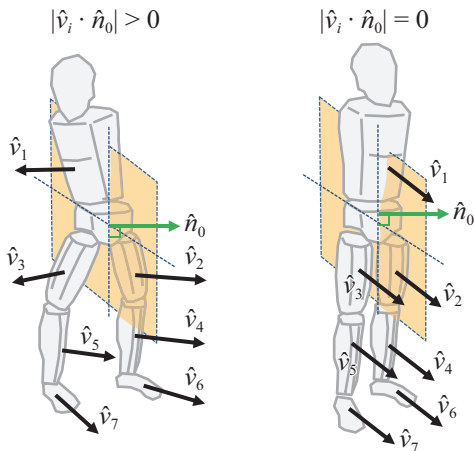


Fig. 4 Objective function for yaw compensation

Jacobian matrix.

$$\text{grad}_{yaw}(Q) = J_{yaw}^T(Q) F_{yaw}(Q) \quad (17)$$

Using the orientation of the whole body Q_t at time t and Eq. (17), the yaw angle compensation amount ΔQ_t can be calculated as follows.

$$\Delta Q_t = \frac{\text{grad}_{yaw}(Q_t)}{\|\text{grad}_{yaw}(Q_t)\|} \quad (18)$$

ΔQ_t is a vector that combines the yaw angle compensation amounts for the IMU of every link, and it is composed as follows with the compensation amount $\Delta e_{i,t}$ of Link i as an element.

$$\Delta Q_t = [\Delta e_{0,t} \ \Delta e_{1,t} \ \Delta e_{2,t} \ \cdots \ \Delta e_{N-2,t} \ \Delta e_{N-1,t}] \quad (19)$$

Factoring Eq. (19) into the elements of each link, compensation for the yaw angle of Link i is obtained by the following equation, as it was for roll and pitch compensation in Eq. (10). However, $\beta_{yaw} > 0$ is the feedback gain for the compensation amount.

$${}^S\dot{e}_{i,t} \leftarrow {}^S\dot{e}_{i,t} - \beta_{yaw} \Delta e_{i,t} \quad (20)$$

2.6. Filter Configuration

The method proposed in the present research (proposed method) can be divided generally into the operations of performing numerical integration of the angular velocities from the individual IMU sensors and calculating the orientation, and the operations of compensating for orientation by means of Eqs. (10) and (20). The former will be explained first. The next equation is used to translate the angular velocities measured using the IMU to a time differential form of quaternion⁽¹¹⁾.

$${}^S\dot{e}_{i,t} = \frac{1}{2} {}^S\hat{e}_{i,t-1} \otimes {}^S\omega_{i,t} \quad (21)$$

$${}^S\omega_{i,t} = [0 \ \omega_{i,t}^x \ \omega_{i,t}^y \ \omega_{i,t}^z] \quad (22)$$

However, ${}^S\omega_{i,t}$ in Eq. (22) is the angular velocity of Link i at time t and it is a four-dimensional vector that has the first element as zero. Using ${}^S\dot{e}_{i,t}$ and the previous value for orientation ${}^S\hat{e}_{i,t-1}$, the orientation is updated as follows. Here, Δt is the sampling time. Since ${}^S\hat{e}_{i,t}$ is not a unit quaternion, attention is paid to the necessity for normalization.

$${}^S\hat{e}_{i,t} = {}^S\hat{e}_{i,t-1} + {}^S\dot{e}_{i,t} \Delta t \quad (23)$$

$${}^S\hat{e}_{i,t} = \frac{{}^S\hat{e}_{i,t}}{\|{}^S\hat{e}_{i,t}\|} \quad (24)$$

The orientation ${}^S\hat{e}_{i,t}$ that has been estimated by the

above calculations is a simple numerical integration of the angular velocities measured by IMU. This estimated orientation ends up diverging over time from the actual orientation because of error in the measurement values. In order to reduce this error, the compensation amounts obtained from Eqs. (10) and (20) are used as shown below as compensation for the angular velocity ${}^S\dot{e}_{i,t}$.

$$\begin{aligned} {}^S\dot{e}_{i,t} = & \frac{1}{2} {}^S\hat{e}_{i,t-1} \otimes {}^S\omega_{i,t} \\ & - \beta_g \frac{\text{grad}_g({}^S\hat{e}_{i,t-1}, {}^S\hat{a}_{i,t})}{\|\text{grad}_g({}^S\hat{e}_{i,t-1}, {}^S\hat{a}_{i,t})\|} \\ & - \beta_{yaw} \Delta e_{i,t-1} \end{aligned} \quad (25)$$

The configuration of the orientation estimation filter that uses the compensation from Eq. (25) is shown in Figs. 5 and 6. Figure 5 corresponds to the operation of integrating the angular velocity of Link i and applying compensation for acceleration to the roll and pitch angles. Figure 6 also shows the operation of determining the yaw angle compensation amount. Here, Q_{t-1} and ΔQ_{t-1} are the previous value for estimated orientation of every link and the yaw angle compensation amount, respectively. The previous value for estimated orientation of every link ${}^S\hat{e}_{i,t-1}$ emerges at ① in Fig. 5 and it is supplied as input to ① in Fig. 6. The estimated orientation ${}^S\hat{e}_{i,t-1}$ of every link is integrated in Q_{t-1} , which is used to calculate the compensation amount ΔQ_{t-1} by means of Eq. (18). This is factored into the yaw angle compensation amount $\Delta e_{i,t-1}$ for every link and supplied as input from ② in Fig. 6 to ② in Fig. 5. In Fig. 5, $\Delta e_{i,t-1}$ is applied as feedback to angular velocity and is reflected as the compensation amount for yaw angle direction.

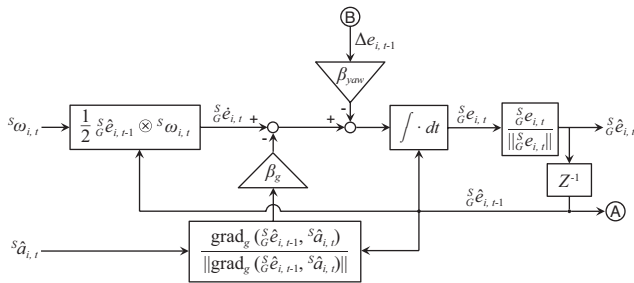


Fig. 5 Block diagram of orientation estimation

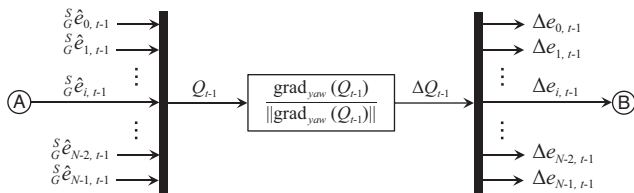


Fig. 6 Block diagram of yaw compensation

3. Experiment

A comparison was made of the proposed method and the previously existing measurement method applied to walking movement. Optical motion capture, which is widely used for motion measurement, was taken as the point of comparison. The IMU and reflective markers for optical motion capture use were attached as shown in Fig. 7 and measurements were performed simultaneously. The MTw Awinda from Xsens was used for the IMU. Angular velocity and acceleration data were acquired through the software development kit provided by the company and the operations for the proposed method were implemented. For optical motion capture, the MAC3D System from nac Image Technology, Inc., was used. Walking measurements were made of two test subjects on a treadmill. Starting from a static standing state, the treadmill speed was raised until the test subjects reached a comfortable walking speed, and measurement of walking was continued for 30 seconds.

It should be noted that this experiment was conducted with the approval of Honda's Bioethics Committee. The experimental subjects participated of their own free will. They had received complete oral and written explanations in advance from the principal investigator regarding the purpose of the present research, its content, and the rights of the participants, and their consent to participate was obtained in writing.

Figure 8 shows the extension and flexion angles at the hip joints and knee joints and the plantarflexion and dorsiflexion angles at the ankle joints for 10 seconds from when walking was started as estimated from the IMU and optical motion capture. In addition, the root mean square (RMS) differences in joint angle between the estimates obtained by the two methods are shown in Table 1. This table shows the RMS of differences in angle calculated for extension and flexion (plantarflexion and dorsiflexion), abduction and adduction, and external and internal rotation for each axis in the hip joints, knee joints, and ankle joints,

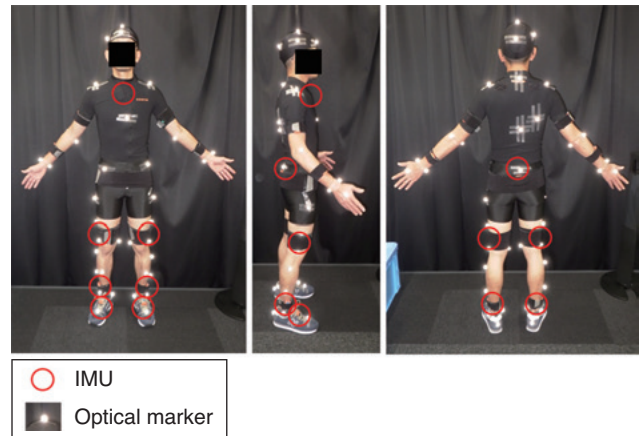


Fig. 7 IMU and optical marker allocation

Table 1 RMS differences between IMU and optical motion capture

Joint		RMS differences [deg]	
		MARG ⁽¹¹⁾	Proposed method
Hip	Extension/ Flexion	4.8	3.8
	Abduction/ Adduction	3.7	4.9
	External/ Internal	5.7	4.4
Knee	Extension/ Flexion	3.7	4.8
	Abduction/ Adduction	4.4	5.1
	External/ Internal	8.4	5.7
Ankle	Plantarflexion/ Dorsiflexion	4.7	5.8
	Abduction/ Adduction	7.2	5.3
	External/ Internal	5.7	8.9

respectively. For the purpose of comparison, the results obtained with measurable geomagnetism in addition to angular velocity and acceleration using a MARG sensor with the Xsens method⁽⁷⁾ are given.

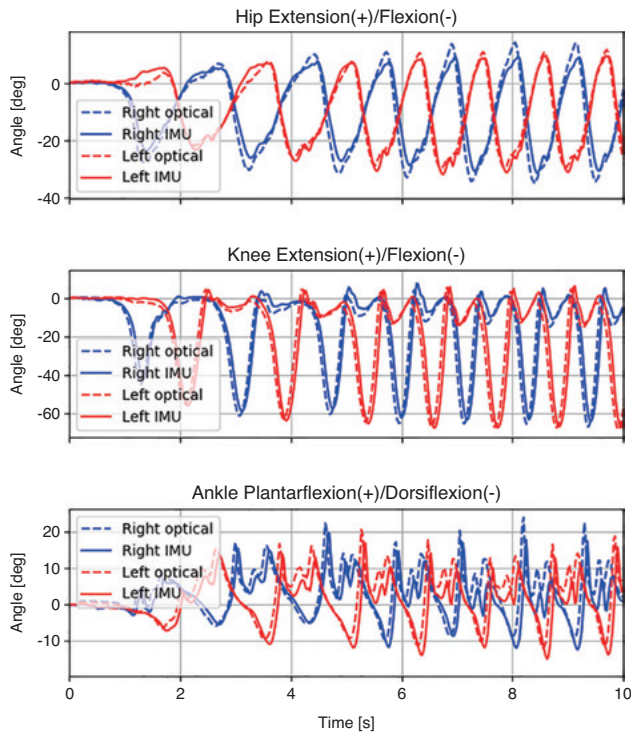


Fig. 8 Comparison of joint angles

Next the effect of reduction in yaw angle error occurring over a long period of measurement was evaluated. This was done by measuring walking that involved a turning movement for a 5-minute period. This movement involved greater angular velocity in the yaw direction than walking straight forward, and the influence of estimation errors would tend to emerge more. The comparison was made between the proposed method and the case in which yaw angle compensation was nullified by assigning a zero value to the feedback gain β_{yaw} for the yaw angle compensation amount described in Section 2.5. Figure 9 shows the internal and external rotation angles for the cases with and without yaw angle compensation.

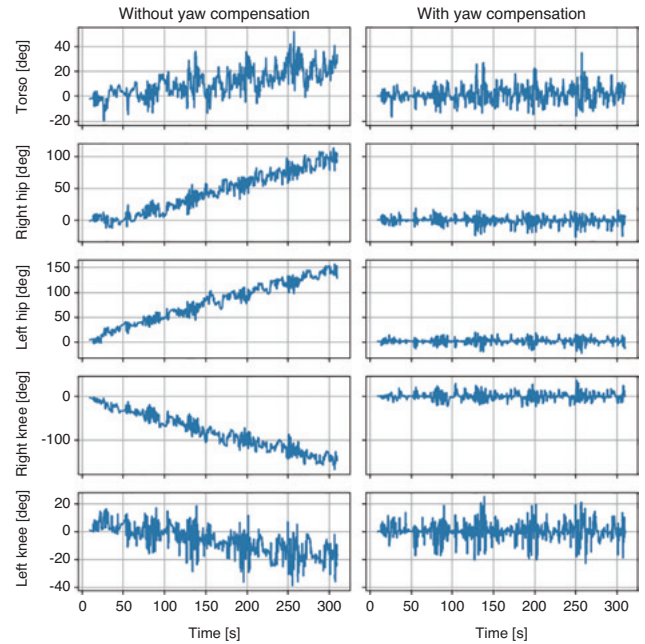


Fig. 9 Comparison of internal/external angles

4. Discussion

The comparison of estimated joint angles in walking movement with the optical motion capture approach (Table 1) showed that the RMS difference in joint angle for the proposed method was from 3.8 to 8.9 deg, which was a result on a par with the RMS from 3.7 to 8.4 deg for the Xsens method using MARG sensors. When the movement is one in which the yaw angles of every link become identical when averaged over time, as is the case with walking movement, the proposed method can be used in the same way as the motion capture systems that are available on the market.

It is also apparent from the results for measurement of walking movement that involved turning (Fig. 9) that when $\beta_{yaw} = 0$ and yaw angle compensation is not implemented,

the amount of drift in the external and internal rotation angles of each joint is large. In the left hip joint, in particular, a drift of 150 deg has occurred in the external rotation direction at a point 300 seconds from the start of measurement. Error in the external and internal rotation angles in the walking movement could not be lessened to a significant extent by roll and pitch angle compensation using the direction of gravity. This extent of drift is thought to result because the bias error in yaw angle direction is reflected so strongly. By contrast, when the yaw angle compensation is activated in the proposed method, this error was resolved to some extent. When walking involves a turning movement, the change in the yaw angle is greater and the influence of inconclusive bias errors becomes greater. The proposed method can reduce the yaw angle drift in the base link coordinate system even under such circumstances, and therefore the external and internal rotation angles show an average transition of 0 deg even after 300 seconds.

5. Conclusion

In order to create a method for estimating motion using only an IMU attached to every link in the body, the measurement object was limited to movement in which the yaw angle of each link ends up in the same direction when averaged over time. A method of yaw angle compensation that takes that limitation as a guide was examined.

An objective function that expresses the extent to which the yaw angles on all the links with an IMU attached coincide was defined, and a compensation direction that reduces that objective function to the lowest level was sought. In this way, a method of compensation for the yaw angle in the base link coordinate system was devised. With regard to walking movement, the RMS of difference between joint angles estimated using conventional IMU and magnetometer and joint angles estimated using optical motion capture is 8.4 deg. The figure for the present method using only an IMU was 8.9 deg, indicating that it is equal in accuracy.

The present research has realized yaw angle compensation in the base link coordinate system for the above measurement object movement that does not depend on a magnetometer, and it is thought that estimation of motion over a long period of time using only the IMU will become possible.

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