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Paper

Measurement of Joint Moments using Wearable Sensors

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Advanced rehabilitation requires a measurement system that quantitatively analyzes the actions of each individual. Joint moment is an indice used to quantitatively evaluate an individual's actions. Conventionally, force plates and high-speed cameras have been used to analyze joint moments. However, these devices need to be fixed in a laboratory, which limits the measurable motions and measurement range. Further, these sensors are expensive. Hence, it is difficult to use them in medical or nursing care facilities. Therefore, this study aimed to estimate joint moments using inexpensive and wearable sensors. This paper proposes a practical joint moments estimation system using inertial measurement units, which is a wearable sensor. The proposed method uses wearable sensors to measure continuous motion without limitation. It is also cheaper than conventional systems. The effectiveness of the proposed system was verified by comparison with the method using force sensors.

Keywords: rehabilitation, IMU, walking phase, floor reaction force, ZMP, joint moment

1. Introduction

In recent years, a declining birthrate and an aging population become a serious social problem in many developed countries [1]. It is expected that the number of care recipients will increase more in the future since the ratio of these people becomes higher as they get older. In order to increase the number of self-support elderly, it is necessary to put intensive effort on health maintaining elderly [2]. From this point of view, the quality of rehabilitation is an important issue. The conventional rehabilitation may not be able to provide individually tailored training as it is based on each physical therapist's knowledge and experience. In addition, it cannot judge quantitatively whether the effect of rehabilitation has come out. Analyzing the motions of each person on a daily basis and providing objective data are desireble [3]. It is known that information of joint moments for lower limbs during walking is useful in a guidance and research of walking rehabilitation [4].

Conventional systems for measuring joint moments utilize a force plate and high speed cameras [5]. The force plate is used to acquire the floor reaction force, and the high-speed camera is used to detect the human posture. Since these analysis systems are used fixedly in a laboratory, measurable ranges and motions are restricted. In addition, they are presently not widely employed in medical sites since they are so expensive.

Recently, several studies have been conducted to solve the problems of these measurement systems. T. Liu *et al.* estimated the floor reaction force under various environments other than the laboratory by attaching multiaxial force sensors to special shoes [6]. It become possible to measure continuous movement like walking by using wearable force sensors. However, the force sensor attached to the sole is very hard and affects natural walking. A force sensor is useful to measure force accurately. However, the measurement range is limited to the place where the sensor is installed, which affects the gait. Therefore, a method to estimate floor reaction force without using a force sensor was proposed. K. Ogata *et al.* estimated the floor reaction force by solving inverse dynamics from the attitude information acquired from a color-depth sensor [7]. In the method using only color-depth sensor, natural walking is not impeded since there is no restriction by force sensors. However, in this method, the measurement range is limited. In addition, only the increase or decrease of the floor reaction force can be estimated, and a joint moment cannot measured.

Therefore, the purpose of this research is to estimate a joint moment using inexpensive and wearable measuring devices. By achieving this goal, a practical system that can be used by many people on a daily basis with fewer limitations of measurement range and measurement actions is realized. In this paper, a joint moment estimation method using inertial measurement units (IMUs) is proposed. IMUs are inexpensive and wearable devices. IMUs detect angular velocity and acceleration of three axes. When estimating the joint moments only with the IMUs, it is difficult to obtain the absolute positions of body segments and floor reaction force.

In this paper, joint moments estimation by IMUs is achieved by solving these problems. The contribution of this paper is as follows. Firstly, the proposed method determines the single supporting phase and the double supporting phase by the acceleration values obtained by IMUs attached to the feet. By determining the phase of walking, it can be determined whether or not the foot is in contact with the floor.

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Secondly, the proposed method separates the total floor reaction force into the floor reaction force of right and left foot using the zero moment point during double supporting phase. Finally, the joint moments are calculated from the experimental data and its effectiveness was verified.

This paper is organized as follows. In section 2, human modeling and forward kinematics used for analysis are explained. In section 3, the method to determine the walking phase is explained. In section 4, a method of estimating floor reaction force based on walking phase is explained. In section 5, the method of estimating ankle and knee joint moments are explained. In section 6, the estimation accuracy of the proposed method is compared with the method using force sensors by experiments. Finally, the conclusion is presented in section 7.

2. Human Body Modeling

This section describes the modeling of the human body for dynamic analysis. Figure 1 shows the human body modeled in the sagittal plane as seven rigid body links consisting of an upper body, thighs, lower legs, and feet [8]. Figure 2 shows the locations and numbers of IMUs. The length L of each link are measured values. The mass m, the length from the central end of the link to the mass center point L_c and the moment of inertia I are estimated from measured height and measured weight [9]. Note that, L_c of the foot is the length from the tip to the center of the mass. The heel is 90 degrees. The joint absolute angles θ can be obtained by integrating the angular velocity $\dot{\theta}$ acquired by IMUs. The joint relative angles q are defined as shown in Fig. 1. The joint relative angles correspond to human ankle joints, knee joints and hip joints. These relative angles are necessary to calculate the joint moments. In this paper, ankle and knee joint moments are calculated. Therefore, it is necessary to calculate the ankle and knee joint angles. The ankle joint angles q_1, q_6 and the knee joint angles q_2, q_5 are calculated as

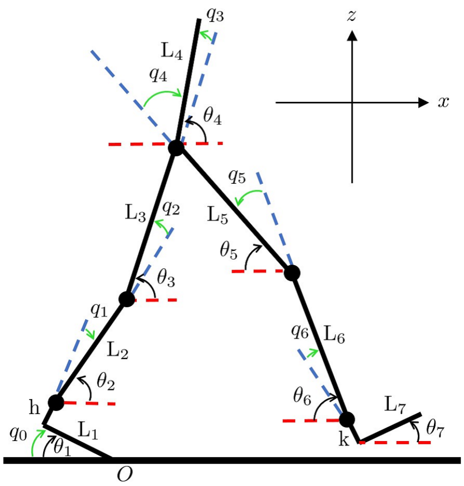

Fig. 1. Rigid body link model of human body

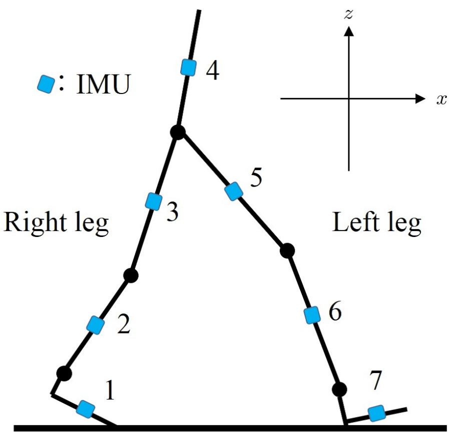

Fig. 2. Locations and numbers of IMUs

$$q_1 = \frac{\pi}{2} - \theta_1 - \theta_2, \quad (1)$$

$$q_2 = \theta_3 - \theta_2, \quad (2)$$

$$q_5 = \theta_6 - \theta_5, \quad (3)$$

$$q_6 = -\frac{\pi}{2} + \theta_6 + \theta_7. \quad (4)$$

The position of each joint X and Z, the center of gravity position of each link X_c and Z_c are obtained by solving forward kinematics using absolute angles θ. Equation (5)–(18) shows the forward kinematics to calculate the link center of gravity positions.

$$X_{c1} = -L_{c1}\cos\theta_1 \quad (5)$$

$$Z_{c1} = L_{c1}\sin\theta_1 \quad (6)$$

$$X_{c2} = -L_1\cos\theta_1 + h\sin\theta_1 + L_{c2}\cos\theta_2 \quad (7)$$

$$Z_{c2} = L_1\sin\theta_1 + h\cos\theta_1 + L_{c2}\sin\theta_2 \quad (8)$$

$$X_{c3} = -L_1\cos\theta_1 + h\sin\theta_1 + L_2\cos\theta_2 + L_{c3}\cos\theta_3 \quad (9)$$

$$Z_{c3} = L_1\sin\theta_1 + h\cos\theta_1 + L_2\sin\theta_2 + L_{c3}\sin\theta_3 \quad (10)$$

$$X_{c4} = -L_1\cos\theta_1 + h\sin\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 + L_{c4}\cos\theta_4 \quad (11)$$

$$Z_{c4} = L_1\sin\theta_1 + h\cos\theta_1 + L_2\sin\theta_2 + L_3\sin\theta_3 + L_{c4}\sin\theta_4 \quad (12)$$

$$X_{c5} = -L_1\cos\theta_1 + h\sin\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 + (L_5 - L_{c5})\cos\theta_5 \quad (13)$$

$$Z_{c5} = L_1\sin\theta_1 + h\cos\theta_1 + L_2\sin\theta_2 + L_3\sin\theta_3 - (L_5 - L_{c5})\sin\theta_5 \quad (14)$$

$$X_{c6} = -L_1\cos\theta_1 + h\sin\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 + L_5\cos\theta_5 + (L_6 - L_{c6})\cos\theta_6 \quad (15)$$

$$Z_{c6} = L_1\sin\theta_1 + h\cos\theta_1 + L_2\sin\theta_2 + L_3\sin\theta_3 - L_5\sin\theta_5 - (L_6 - L_{c6})\sin\theta_6 \quad (16)$$

$$X_{c7} = -L_1\cos\theta_1 + h\sin\theta_1 + L_2\cos\theta_2 + L_3\cos\theta_3 + L_5\cos\theta_5 + L_6\cos\theta_6 + k\sin\theta_7 + (L_7 - L_{c7})\cos\theta_7 \quad (17)$$

$$Z_{c7} = L_1\sin\theta_1 + h\cos\theta_1 + L_2\sin\theta_2 + L_3\sin\theta_3 - L_5\sin\theta_5 - L_6\sin\theta_6 - k\cos\theta_7 + (L_7 - L_{c7})\sin\theta_7 \quad (18)$$

3. Discrimination Method of Walking Phase

This section describes how to determine the phase of walking. To calculate joint moments by dynamics calculation, it is necessary to estimate the floor reaction force accurately.

Since the floor reaction force is applied to the leg only when it is in contact with the floor, it can be determined whether the floor reaction force is applied by the walking phase. In this paper, the right leg supporting phase, the left leg supporting phase, and the double supporting phase are defined as the phase of walking. The walking phase is determined by using the absolute values of accelerations and angular velocities of the feet. In the single supporting phase, the absolute values of the accelerations and the angular velocities of the free leg are large. These are due to the swinging motion of the free leg. On the other hands, the absolute values of the accelerations and the angular velocities of the supporting leg are small. These are because the supporting legs are fixed. In double supporting phase, since a rotation motion occurs on both ankles, the accelerations and angular velocities increase. Therefore, if the acceleration magnitude thresholds S_a and angular velocity threshold $S_{\dot{\theta}}$ are determined, the walking phase can be identified by the discriminant functions shown in (19)–(22).

$$if\ double\ supporting\ phase$$

$$\sqrt{a_{x1}^2+(a_{z1}-g)^2} > S_{a_1} \wedge |\dot{\theta}_1| > S_{\theta_1} \wedge \sqrt{a_{x7}^2+(a_{z7}-g)^2} > S_{a_7} \wedge |\dot{\theta}_7| > S_{\dot{\theta}_7} \quad \cdots\cdots\cdots (19)$$

$$if\ left\ leg\ supporting\ phase$$

$$\sqrt{a_{x1}^2+(a_{z1}-g)^2} > S_{a_1} \wedge |\dot{\theta}_1| > S_{\theta_1} \wedge \sqrt{a_{x7}^2+(a_{z7}-g)^2} \le S_{a_7} \wedge |\dot{\theta}_7| \le S_{\dot{\theta}_7} \quad \cdots\cdots\cdots (20)$$

$$if\ right\ leg\ supporting\ phase$$

$$\sqrt{a_{x1}^2+(a_{z1}-g)^2} \le S_{a_1} \wedge |\dot{\theta}_1| \le S_{\theta_1} \wedge \sqrt{a_{x7}^2+(a_{z7}-g)^2} > S_{a_7} \wedge |\dot{\theta}_7| > S_{\dot{\theta}_7} \quad \cdots\cdots\cdots (21)$$

$$if\ standing\ still$$

$$\sqrt{a_{x1}^2+(a_{z1}-g)^2} \le S_{a_1} \wedge |\dot{\theta}_1| \le S_{\theta_1} \wedge \sqrt{a_{x7}^2+(a_{z7}-g)^2} \le S_{a_7} \wedge |\dot{\theta}_7| \le S_{\dot{\theta}_7} \quad \cdots\cdots\cdots (22)$$

g is the gravitational acceleration. The acceleration of a_x, a_z and the angular velocity $\dot{\theta}$ are measured by IMUs. When (19) is satisfied, double supporting phase is determined. When (20) or (21) are satisfied, single supporting phase is determined. Furthermore, when (20) is satisfied, it is the left leg supporting phase, and when (21) is satisfied, it is the right leg supporting phase. If standing still, it is determined by (22). Thus, the phase of walking can be determined from the characteristics of walking that occur in the feet. The reason why both accelerations and angular velocities are used is to improve the determination accuracy. Also, it is not necessary to use other sensors since both are obtained from IMUs.

4. Estimation Method of Floor Reaction Force

In this section, a method for estimating floor reaction force during walking is described. In this paper, only the floor reaction force in the direction of gravity is considered for the

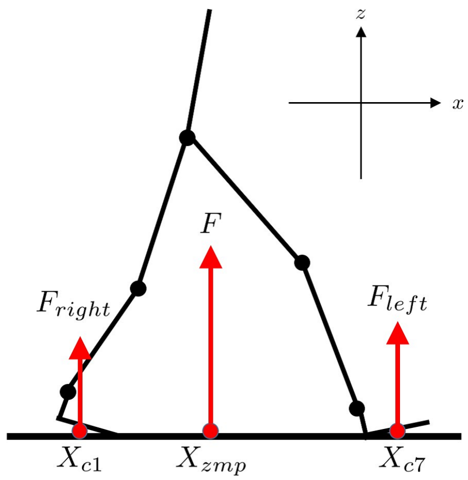

Fig. 3. Overview of floor reaction force

evaluation. Note that the floor reaction force in the walking direction is not considered due to the limitation of the experimental system. Figure 3 shows an overview of the floor reaction force. The floor reaction force is calculated by the equation of motion using the accelerations obtained from the IMUs attached to each link and the weight of each link estimated from the body weight. The total floor reaction force F of both feet is derived from the acceleration and the mass of each link by the equation of motion shown as

$$F = \sum_{i=1}^{7} m_i(g + a_{zi}). \quad \cdots\cdots\cdots (23)$$

In the single supporting phase, the total floor reaction force of both feet is applied only to the supporting foot. Therefore, the floor reaction force applied to the supporting foot is the total floor reaction force F of both feet. In the double supporting phase, both the left foot and right foot are in contact with the floor. Therefore, it is necessary to separate the total floor reaction force into the floor reaction force of the left foot and the right foot. In this paper, the zero moment point (ZMP) is used to separate the total floor reaction force into the left foot and the right foot [10]. ZMP is the point of action when the normal component of the floor reaction force distributed across the entire foot sole has been replaced as lying on a certain point. It is known that the ZMP coincides with the center of pressure (COP). Assuming that the floor reaction forces are applied to the COP of the right foot and the COP of the left foot, the total floor reaction force can be separated using the length ratio from ZMP to the COP of the right foot and the COP of the left foot. However, the proposed measurement system cannot measure the COP of each foot. In normal walking, the COP of the right foot and the left foot are within the contact surface of the feet and ground. Therefore, the following is assumed to estimate the floor reaction forces. It is assumed that walking is static during double supporting phase, and the COP and foot center of gravity are close to each other. By considering in this way, the floor reaction forces applied to the left and right legs are estimated using the feet center of gravity instead of the COP. ZMP is shown in (24) [11]. Using ZMP X_{zmp}, feet center of gravity position X_{c1}, X_{c7} the floor reaction force of left foot and right foot F_{right}, F_{left} are expressed as

$$X_{zmp} = \frac{\sum_{i=1}^{n} m_i(X_i(a_{zi}+g) - Z_i a_{xi}) - \sum_{i=1}^{7} I_i \ddot{\theta}_i}{\sum_{i=1}^{7} m_i(a_{zi}+g)}, \quad (24)$$

$$F_{right} = \frac{X_{c7} - X_{zmp}}{X_{c7} - X_{c1}} F, \quad (25)$$

$$F_{left} = \frac{X_{zmp} - X_{c1}}{X_{c7} - X_{c1}} F. \quad (26)$$

5. Estimation Method of Joint Moments

In this section, a method for estimating joint moment during walking is described. Figure 4 shows the factors affecting the ankle joint moment. The ankle joint moment τ_a can be calculated as [12]

$$\tau_a = I_f \ddot{q}_a + m_f a_{xf}(Z_a - Z_{fc}) + m_f a_{zf}(X_a - X_{fc}) - F_f(X_F - X_a). \quad (27)$$

Equation (27) takes into consideration of the acceleration a_{xf}, a_{zf} occurring at the center of gravity of the foot, the angular acceleration $\ddot{q}_a$ occurring at the ankle, and the z-direction floor reaction force F_f applied to the foot. In this paper, the floor reaction force in the walking direction is not considered, so the joint moment generated by the floor reaction force in the walking direction is not included. q_a corresponds to q_1 and q_6 shown in Fig. 1. X_a and Z_a are the position of the ankle, X_{fc} and Z_{fc} are the center of gravity of the foot, and X_F and Z_F are floor reaction force application points, I_f is the moment of inertia of the foot, m_f is the mass of foot. Similarly, the knee joint moment τ_k can be obtained as

$$\tau_k = I_k \ddot{q}_k + \left(m_l a_{xl}\frac{L_{lc}}{L_l} + m_f a_{xf}\right)(Z_k - Z_a) + \left(F_f - m_l a_{zl}\frac{L_{lc}}{L_l} - m_f a_{zf}\right)(X_a - X_k) + \tau_a. \quad (28)$$

a_{xl}, a_{zl} are the accelerations of lower leg, $\ddot{q}_k$ is the angular acceleration of the knee, L_l is the length of lower leg, L_{lc} is the length from the central end of the link to the center of the mass, X_k and Z_k are the position of the knee, I_k is the moment of inertia of the knee, m_l is the mass of lower leg. q_k corresponds to q_2 and q_5 shown in Fig. 1. During walking, the floor reaction force application point transitions from heel to toe. Note that, this paper assumes that the action point of the floor reaction force transits linearly from the heel to the toe in the support phase.

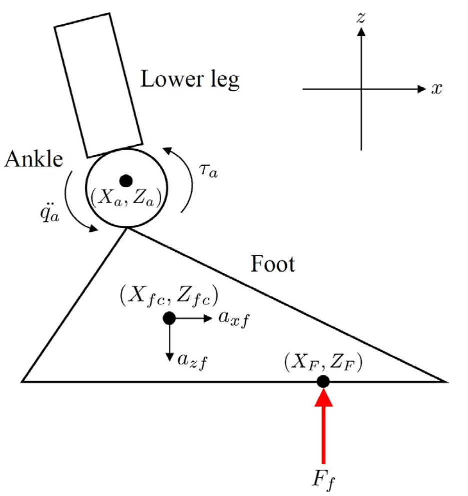

Fig. 4. Estimation method of ankle joint moment

6. Walking Experiments

This section describes walking experiments. The subject's free walk was analyzed. Proposed method was compared with the method using force sensors to verify the effectiveness.

6.1 Experimental Setup In the experiment, a 24-year-old healthy woman walked at a free speed. Table 1 lists the subject's physical parameters. Seven IMUs, TSND151 (ATR-Promotions, Japan), were used and attached to the upper body, thighs, lower legs, and feet respectively. IMU includes accelerometers, gyroscopes, a magnetometer, and a pressure sensor. In addition, the force sensors, medilogic Foot Pressure Measuring System (T&T medilogic Medizintechnic GmbH), were used to compare with the proposed method. These force sensors were used to measure the floor reaction forces in the z-axis direction. IMUs should be attached to the center of mass positions of each link. However, the exact center of masses are inside the links. For this reason, the IMUs cannot be attached to the exact center of mass positions. Therefore, IMUs were attached at the positions considering the center of mass positions. In the upper body, IMU was attached to the back. Also, IMUs were attached to the outside of the sagital plane of the thighs, lower legs, and feet. The subject with sensors is shown in Fig. 5. From the walking data of the subject, firstly, walking phase is determined. Then floor reaction force is estimated. Finally, joint moments are calculated.

6.2 Discrimination Result of Walking Phase The walking phase was determined by using the absolute values of the accelerations and the absolute values of the angular velocities generated at the feet. The absolute values of accelerations and angular velocities of the feet obtained from IMUs are shown in Fig. 6 and Fig. 7. These calculated values were used in (19)–(22) for walking phase discrimination. In Fig. 6 and Fig. 7, the absolute values of accelerations and angular velocities increase and decrease periodically during walking. This occurs because the swing phase and the stance phase occurs alternately. The results of discrimination of the walking

Table 1. Subject's physical parameters

Parameter	Value
Age	24
Sex	female
Height	1.56 m
Weight	55.0 kg
Upper body length L_4	0.86 m
Thigh length L_3, L_5	0.36 m
Lower leg length L_2, L_6	0.36 m
Foot length L_1, L_7	0.23 m
Upper body mass m_4	34.4 kg
Thigh mass m_3, m_5	6.77 kg
Lower leg mass m_2, m_6	2.92 kg
Foot mass m_1, m_7	0.61 kg
Upper body moment of inertia I_4	1.41 kgm^2
Thigh moment of inertia I_3, I_5	5.89×10^{-2} kgm^2
Lower leg moment of inertia I_2, I_6	1.97×10^{-2} kgm^2
Foot moment of inertia I_1, I_7	1.69×10^{-4} kgm^2

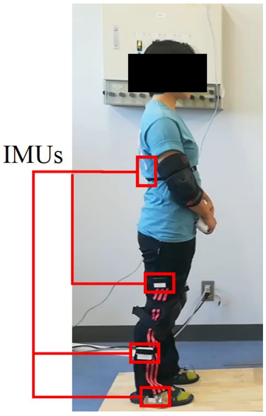

Fig. 5. The subject with sensors

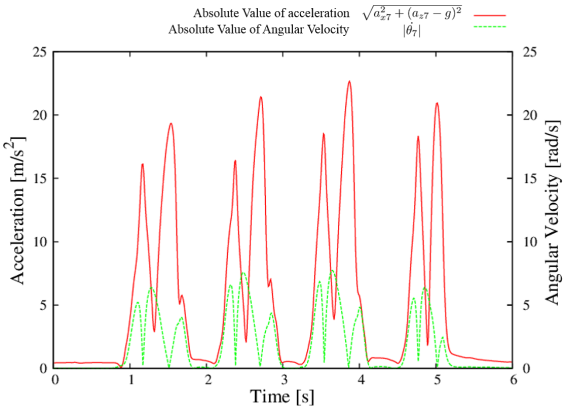

Fig. 6. Absolute values of acceleration and angular velocity of the right foot

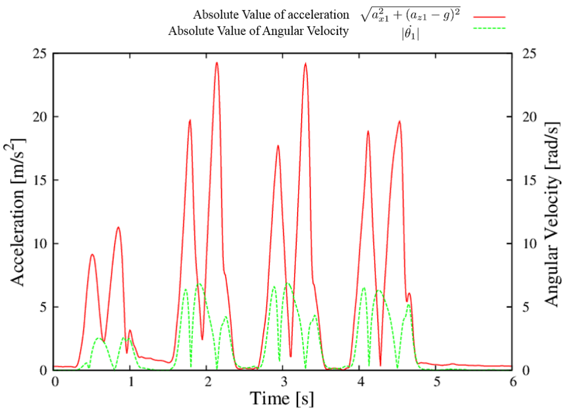

Fig. 7. Absolute values of acceleration and angular velocity of the left foot

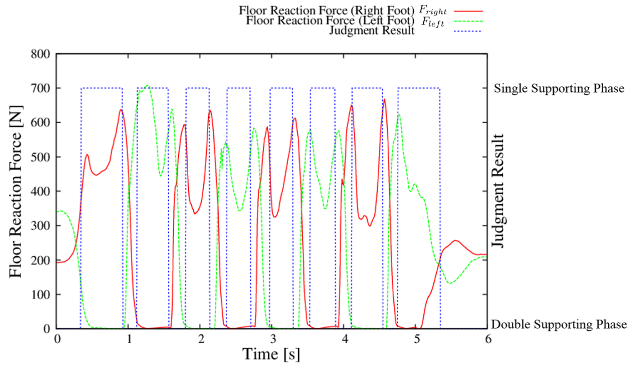

Fig. 8. Determination result of walking phase and measured floor reaction force

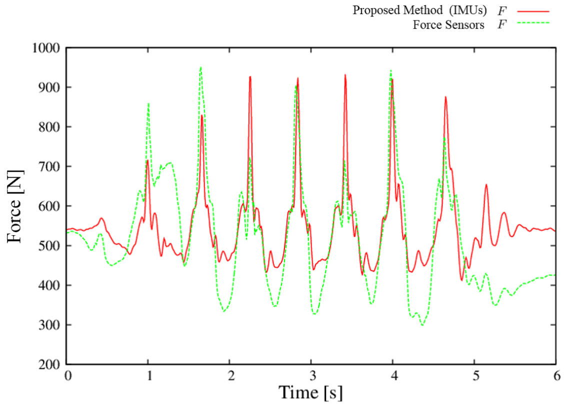

Fig. 9. Total floor reaction force

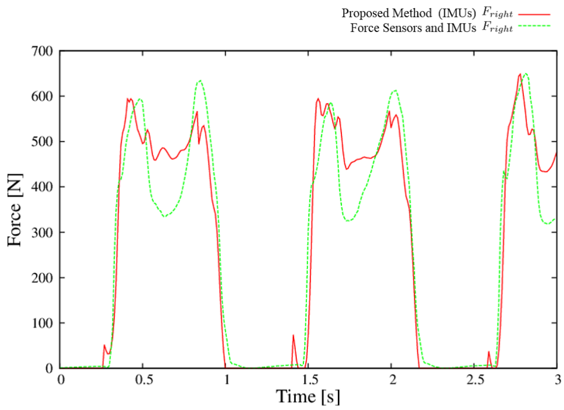

Fig. 10. Floor reaction force (right foot)

phase using the (19)–(22) are shown in Fig. 8. The red line indicated the floor reaction force of the right foot, the green line indicated the floor reaction force of the left foot, and the blue line indicated the walking phase discrimination result. It was determined that there was a single support phases when floor reaction force occurred only on one foot. In addition, it was determined that there was a double support phases when floor reaction force occurred on both feet. The error RMS with the result using a force sensors was 0.02 seconds, and the maximum error was 0.06 seconds. It can be understood from these results that the walking phase can be determined properly.

6.3 Estimation Results of Floor Reaction Force

Figure 9 shows the total floor reaction force obtained from the mass and accelerations of each link. The estimation error RMS per walking cycle was 90.18 N, and the maximum error was 252.18 N. The timing of the increase and decrease of the floor reaction force was the same. The correlation of the waveforms was confirmed. Next, the result of separating the floor reaction force into left and right feet using ZMP is shown in Fig. 10. Figure 10 shows the results of floor reaction force applied to the right foot. The estimation error RMS of the floor reaction force per walking cycle was 73.44 N, the maximum error was 160.20 N, and the correlation coefficient between the proposed method and the method using force sensors was 0.952. A strong correlation of the waveforms was confirmed. Possible causes of the error include that the force sensor was not pressed correctly during walking, and errors of human model parameters such as link length and inertia. The floor reaction forces were estimated using (23)–(26). The accelerations used in these equations were measured with IMUs. The difference between the IMUs positions and the actual center of masses, and vibration of IMUs during walking may affect the accelerations error. These accelerations error may also affect the estimation error of the floor reaction forces. Furthermore, the total floor reaction force was separated into the floor reaction forces of the right leg and the left leg using ZMP and the feet center of gravity positions during the double supporting phase. Using the center of gravity instead of the COP of each foot is one of the causes of the estimation error.

6.4 Estimation Results of Joint Moment The joint moment was calculated from the floor reaction force and the posture information acquired by IMUs. Figures 11 and 12 show the results of the ankle joint moment and knee joint moment. The estimation error RMS of the right ankle joint moment was 4.68 Nm, the maximum error was 11.29 Nm, and the correlation coefficient between the proposed method and the method using force sensors was 0.952. The estimation error RMS of the right knee joint moment was 8.77 Nm, the maximum error was 25.61 Nm, and the correlation coefficient between the proposed method and the method using force sensors was 0.737. The strong consistency of the waveforms was confirmed by the method using the force sensor and the proposed method. As a factor of error, estimation error of floor reaction force can be considered. In particular, since the knee joint had a long distance from the floor reaction force application point, the error of the floor reaction force had a greater influence than the ankle joint.

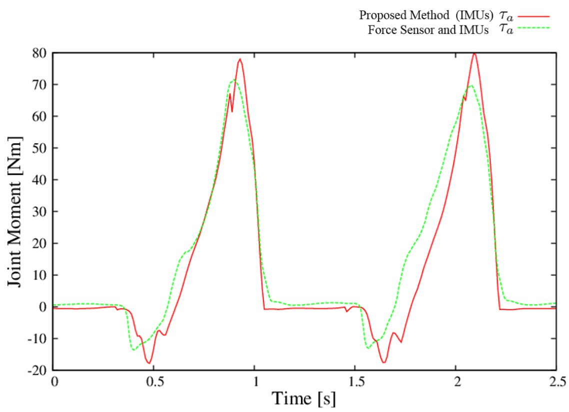

Fig. 11. Right ankle joint moment

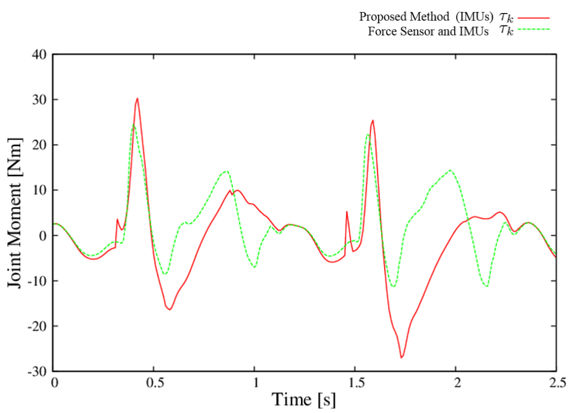

Fig. 12. Right knee joint moment

7. Conclusion

This paper proposes a estimation method of joint moments in walking by using inexpensive and wearable sensors. The important points of the proposed method are the discrimination of walking phase, estimation of the floor reaction force, and estimation of joint moments using only IMUs. The proposed estimation system has several advantages. The proposed estimation system does not require a force sensor. This makes it possible to measure gait without interrupting natural movement. Also, the cost is low and practical. Furthermore, there is no limitation of the measurement range since proposed system uses wearable sensors. The unrestricted measurement range is important when measuring continuous movement, such as walking. In order to confirm the effectiveness of the proposed method, with the method using force sensors. A comparative experiment was conducted. Although the proposed method uses the inexpensive and wearable sensor system, it shows the consistency of the waveform with the method using force sensors. The effectiveness of the proposed method was confirmed from the results. Future work will include improving estimation accuracy. In particular, consideration of the force in the walking direction is a future work. Although the force in the walking direction is small compared to the force in the direction of gravity, it is important in walking because it is a propelling force for walking. It is expected that this practical system could be applied to the medical field such as walking rehabilitation in the future.

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