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Measurement of three-dimensional posture and trajectory of lower body during standing long jumping utilizing body-mounted sensors*

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Abstract—**The measurement method of three-dimensional posture and flying trajectory of lower body during jumping motion using body-mounted wireless inertial measurement units (WIMU) is introduced. The WIMU is composed of three-dimensional (3D) accelerometer and gyroscope of two kinds with different dynamic range and one 3D geomagnetic sensor to adapt to quick movement. Three WIMUs are mounted under the chest, right thigh and right shank. Thin film pressure sensors are connected to the shank WIMU and are installed under right heel and tiptoe to distinguish the state of the body motion between grounding and jumping. Initial and final postures of trunk, thigh and shank at standing-still are obtained using gravitational acceleration and geomagnetism. The posture of body is determined using the 3D direction of each segment updated by the numerical integration of angular velocity. Flying motion is detected from pressure sensors and 3D flying trajectory is derived by the double integration of trunk acceleration applying the 3D velocity of trunk at takeoff. Standing long jump experiments are performed and experimental results show that the joint angle and flying trajectory agree with the actual motion measured by the optical motion capture system.**

I. INTRODUCTION

The measurement system of body movement using body-mounted sensors such as accelerometer, gyroscope and geomagnetic sensor is widely investigated for gait analysis, evaluation of sports performance, game controller and so on[1]. Takede *et al.* proposed gait posture estimation method using inertial sensors, in which the angle of each segment such as thigh and shank is calculated from the integration of the angular velocity and the position of each joint such as hip, knee and ankle is decided sequentially from ankle which touches on the ground to the upper body using the angle and the length of each segment[2]. However, when the foot is apart from the ground and whole body is in the air like standing long jumping[3], the vertical and horizontal position of body cannot be determined from the angle of each segment. To obtain 3D trajectory as well as the posture of body in the air, twice integration of body acceleration in addition to the integration of angular velocity must be calculated. However, few researches have tried to measure the 3D trajectory of the posture apart from the ground using body-mounted sensors because the double integration of the acceleration with small error and wrong estimation of sensor axis cause considerable error in the estimated position[4]. To overcome the effect of the integration error, the authors have proposed the modification method of measured acceleration and the precise estimation method of gait trajectory and pitching motion using body-mounted sensor[5][6].

In this study, by applying the modification method of the acceleration to the flying body, the measurement method of the 3D trajectory and posture of lower body during jumping motion is proposed. Wireless inertial measurement unit (WIMU) is newly developed to acquire 3D acceleration, angular velocity and terrestrial magnetism of three locations of lower body (trunk, thigh and shank). Moreover grounding condition of foot is measured using pressure sensor to detect the foot being apart from the ground and to select the computational algorithm of body trajectory. Estimated posture and trajectory are compared with the optical motion capture system to evaluate the proposed method.

II. PRINCIPLE

A. Model of lower body

Fig.1 shows the three segmental model of lower body used in this study. Notations B, P, H, K, A, T and S indicate body center, pelvis, hip joint, knee joint, ankle joint, thigh and shank, respectively. Lower limbs of right side are considered and those of left side are ignored for simplicity. The length of trunk, thigh and shank are l_B, l_T and l_S. Frame matrices (FM) E_B, E_T and E_S represent the posture of the WIMU mounted on trunk, thigh and shank and are composed of three orthogonal 3D unit vectors i, j and k as follows,

$$E_B(n)=[i_B \quad j_B \quad k_B], \tag{1}$$

$$E_T(n)=[i_T \quad j_T \quad k_T], \tag{2}$$

$$E_S(n)=[i_S \quad j_S \quad k_S]. \tag{3}$$

The direction of 3D vectors i, j and k corresponds with x, y and z axis of sensors installed. Three WIMUs are mounted on the chest, right thigh and right shank so that y-axis (j in FM) of WIMU coincides with the longitudinal axis of each segment toward distal direction and z-axis points front of body. The 3D posture of each segment is determined using the length of segment and j_B, j_T and j_S, and 3D posture of the lower body is eventually obtained by connecting each segment at hip and knee.

B. Estimation method of posture on the ground

The initial posture of trunk during standing still is determined by the FM of trunk E_B which is calculated using

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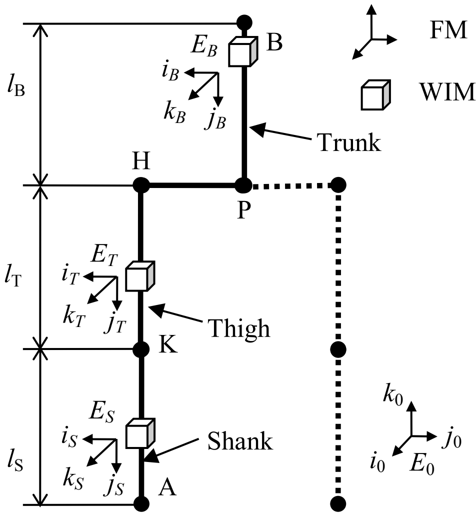

Fig.1 Three segment model of lower body

the 3D acceleration of gravity $a=(a_x\ a_y\ a_z)^T$ and geomagnetism $m=(m_x\ m_y\ m_z)^T$ as follows,

$$E_B = \begin{bmatrix} \cos\theta_m & -\sin\theta_m & 0 \\ \sin\theta_m & \cos\theta_m & 0 \\ 0 & 0 & 1 \end{bmatrix} {}^gE, \tag{4}$$

where

$$ {}^gE = \begin{bmatrix} \cos\theta_x & -\tan\theta_x \sin\theta_y & -\tan\theta_x \sin\theta_z \\ 0 & \sin\theta_z / \cos\theta_x & -\sin\theta_z / \cos\theta_y \\ \sin\theta_x & \sin\theta_y & \sin\theta_z \end{bmatrix}, \tag{5}$$

$$\theta_x = \sin^{-}\frac{a_x}{g},\quad \theta_x = \sin^{-}\frac{a_y}{g},\quad \theta_x = \sin^{-}\frac{a_z}{g},\quad \theta_m = \tan^{-1}\frac{{}^gm_y}{{}^gm_x}, \tag{6}$$

$$ {}^gm = \left({}^gm_x\quad {}^gm_y\quad {}^gm_z\right)^T = {}^gEm\ . \tag{7}$$

The FM ${}^gE$ is derived using a and E_B is obtained by rotating ${}^gE$ around vertical axis so that the azimuthal angle θ_m of terrestrial magnetism ${}^gm$ based on ${}^gE$ agrees to north based on the global coordinate system. Meanwhile, the FMs of thigh and shank (E_T and E_S) during standing still are firstly calculated using acceleration of gravity using (1) and then these are rotated around vertical axis so that horizontal components of k_T and k_S become parallel to that of k_B for easy installation and calculation. When the foot touches the ground before take-off, the 3D position of ankle A is set to the origin $(0\ 0\ 0)^T$, and the 3D positions of knee joint K, hip joint P and body center B are sequentially obtained using the following equations,

$$K(t) = A(t) - l_S j_S, \tag{8}$$

$$P(t) = K(t) - l_T j_T, \tag{9}$$

$$B(t) = P(t) - l_B j_B. \tag{10}$$

During the movement such as flexion of knee before jump, the FM $E(n)$ at the nth sampling period is updated every sampling period Δt using angular velocity $\omega=(\omega_x\ \omega_y\ \omega_z)^T$ measured on the body as follows,

$$E(n+1) = E(n)R, \tag{11}$$

where R is a rotation matrix which rotates $E(n)$ around angular velocity vector ω by θ and is expressed as follows,

$$R = \begin{bmatrix} C_\theta + \lambda^2 V_\theta & \lambda\mu V_\theta - \upsilon S_\theta & \upsilon\lambda V_\theta + \mu S_\theta \\ \lambda\mu V_\theta + \lambda S_\theta & C_\theta + \lambda^2 V_\theta & \lambda\upsilon V_\theta - \lambda S_\theta \\ \upsilon\lambda V_\theta & \mu\upsilon V_\theta + \lambda S_\theta & C_\theta + \lambda^2 V_\theta \end{bmatrix}, \tag{12}$$

$$S_\theta = \sin\theta,\quad C_\theta = \cos\theta,\quad V_\theta = 1 - \cos\theta\ , \tag{13}$$

$$\theta = \omega(n)\Delta t,\quad [\lambda\quad \mu\quad \upsilon]^T = \omega / \|\omega\|\cdot \tag{14}$$

At the moment of landing, the vertical position of the ankle is set to zero. Meanwhile the horizontal position of ankle is obtained applying the position of body center and connecting the thigh and the shank mentioned below.

C. Estimation method of posture in the air

When the right foot is apart from the ground, it is assumed that the subject's body is in the air. The position of body center B is calculated by the double integration of body acceleration a as follows,

$$v(t) = \int_{T_1}^{t} E_B(\tau)a(\tau)\mathrm{d}\tau + v_0\ , \tag{15}$$

$$B(t) = \int_{T_1}^{t} v(\tau)\mathrm{d}\tau + B_0\ , \tag{16}$$

where T_1 is the time of heel off (takeoff) and the integral interval lasts until the landing time T_2. The velocity of body center is v and the initial velocity at takeoff v_0 is obtained by the numerical differentiation of the position of body center B at takeoff. Then the 3D positions of H, K, and A are calculated by the following equations,

$$H(t) = B(t) + l_B j_B, \tag{17}$$

$$K(t) = H(t) + l_T j_T, \tag{18}$$

$$A(t) = K(t) + l_S j_S\ . \tag{19}$$

D. Modification method of integration error

Because the noise of the measured acceleration such as sensor drift causes velocity error and results in huge position error, it is essential to remove the integration error for the precise estimation of trajectory during jumping. In this study, the vertical position of the ankle $A_{z1}(t)$ including integration error is modified using the estimated vertical distance $A_{z1}(T_2)$ at heel contact so that the vertical distance reaches to zero. The modified vertical position of ankle $A_{z2}(t)$ is expressed as

$$A_{Z2}(t) = A_{Z1}(t) - \frac{A_{Z1}(T_2)}{T_2 - T_1}(t - T_1)\quad (T_1 \le t \le T_2)\cdot \tag{20}$$

In addition, the FM is affected by the integration error of angular velocity. The erroneous FM is modified so that the FM at the end of the movement agrees to the FM obtained using gravitational acceleration and geomagnetism applying an equivalent rotation matrix during the movement[5].

E. Evaluation of estimated posture and trajectory

Assuming that the subject performs straightforward jumping, x, y and z-axis of the coordinate system based on the sagittal plane ${}^S\Sigma$ are defined as the direction of movement, left-hand side and vertical direction, respectively. As shown in Fig.2, the validity of the proposed method is confirmed by

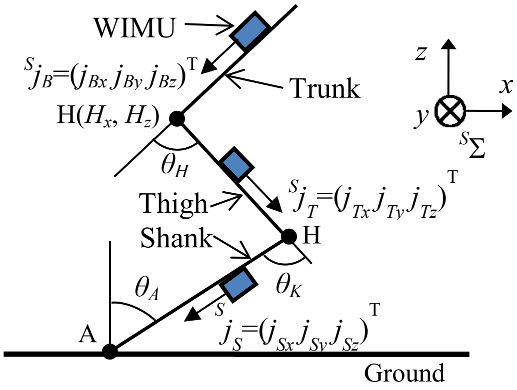

Fig.2 Definition of joint angles

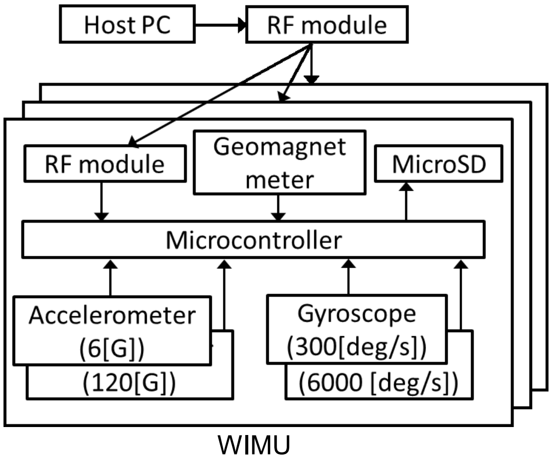

Fig.3 Block diagram of measurement system

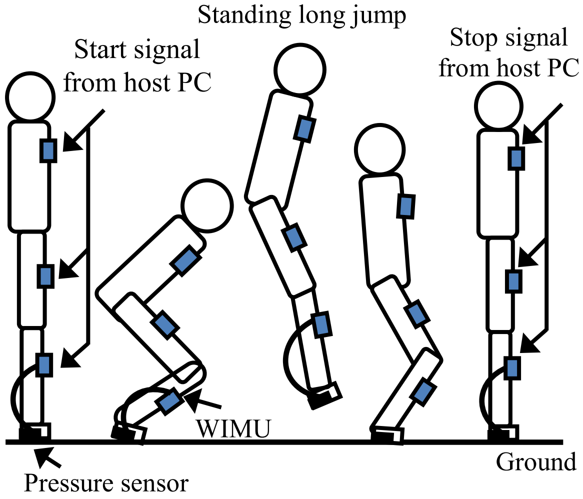

Fig.4 Overview of experiment

comparing the hip joint angle θ_H, knee joint angle θ_K and ankle joint angle θ_A projected on the sagittal plane between the proposed method and the result obtained from the optical motion capture system (MCS). Unit vectors ${}^{S}j_B=(j_{Bx}\, j_{By}\, j_{Bz})^{\mathrm{T}}$, ${}^{S}j_T=(j_{Tx}\, j_{Ty}\ j_{Tz})^{\mathrm{T}}$ and ${}^{S}j_S=(j_{Sx}\, j_{Sy}\, j_{Sz})^{\mathrm{T}}$ are conversion of j_{B}, j_{T} and j_{S} to ${}^{\mathrm{S}}\Sigma$. The angles θ_H, θ_K, and θ_A are derived as

$$\theta_H = \tan \frac{j_{Tz}}{j_{Tx}} - \tan \frac{j_{Bz}}{j_{Bx}}, \tag{21}$$

$$\theta_K = \tan \frac{j_{Tz}}{j_{Tx}} - \tan \frac{j_{Sz}}{j_{Sx}}, \tag{22}$$

$$\theta_A = \tan \frac{-j_{Sx}}{-j_{Sz}}. \tag{23}$$

In addition to the joint angles, vertical and horizontal displacement of the hip joint H_Z and H_X are compared with the position measured by MCS for the evaluation of jumping trajectory in the air.

III. EXPERIMENT

A. *Experimental equipment*

Fig.3 shows the block diagram of the measurement system. The WIMU is composed of two kinds of 3D accelerometers (Freescale Semiconductor, MMA7361L, 6 G, Analog Devices, ADXL193, 120 G) and 3D gyroscopes (Murata, ENC-03RC, 300 deg/s, STMicroelectronics, LPR5150AL, LPY5150AL, 6000 deg/s) for wide dynamic range measurement, a 3D geomagnetic sensor (Honeywell, HMC5883L), an RF module (XBee, Digi International Ins,) for wireless control of data acquisition, and microcontroller for data acquisition and data storage to microSD card. By broadcasting control signal from a host computer to all WIMUs, synchronized data acquisition of start and finish is achieved[6]. Sampling frequency is set to 100 Hz. As shown in Fig. 4, three WIMUs are fixed under the chest, front of right thigh, and front of right shank using Velcro fastening. The WIMU mounted on the shank is connected to the thin film pressure sensor stuck under the heel and the tiptoe for the detection of grounding condition of foot. The precision of estimated position and joint angle of the lower body is evaluated by using the optical motion capture system (Motion Analysis, MAC3D). Four reflective markers are mounted on greater trochanter, lateral epicondyle, lateral malleolus and abdomen for the comparison of the jumping motion and their 3D positions are sampled at 100 Hz.

B. *Experimental method*

One healthy male subject (age 23 yr, height 175 cm, weight 56 kg) participated in the experiment. Length l_B, l_T and l_S are 0.402m, 0.367m and 0.607m, respectively. As shown in Fig.4 the subject is asked to perform standing long jump with 1 m flight distance four times. The subject stops moving and stands still for a few seconds before and after the jumping, because of the determination of static posture.

IV. RESULT

Fig.5 shows an example of the comparison of the displacement of hip joint H_Z and H_X and joint angles θ_H, θ_K and θ_A between MCS and WIMU. The joint angles are set to 0 at the initial posture. The perpendicular black lines show the time of heel off (1.36 s) and heel contact (2.10 s), respectively. Knee flexion began around 0.5 s and reached to the maximum flexion at 1.21 s. After that the hip joint moved diagonally forward with the extension of hip and knee joints, and went up to the highest position at 1.78 s. From the time of the highest position the knee joint had been extended until heel contact, meanwhile the hip joint was being flexed until after heel contact. Just before heel contact, the knee and ankle joint angles increased rapidly to prepare for landing. After the heel

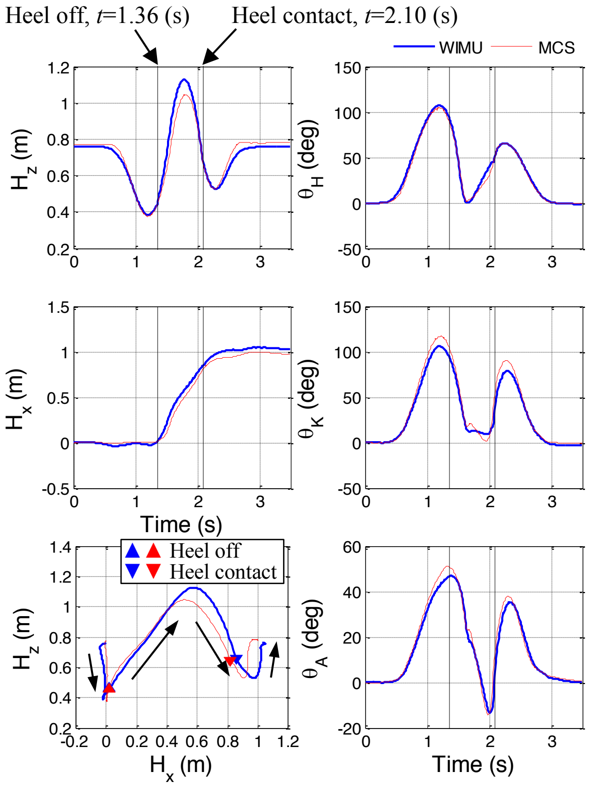

Fig.5 Comparison of the vertical displacement H_Z and horizontal one H_X of hip joint, joint angles of hip, knee and ankle θ_H, θ_K and θ_A

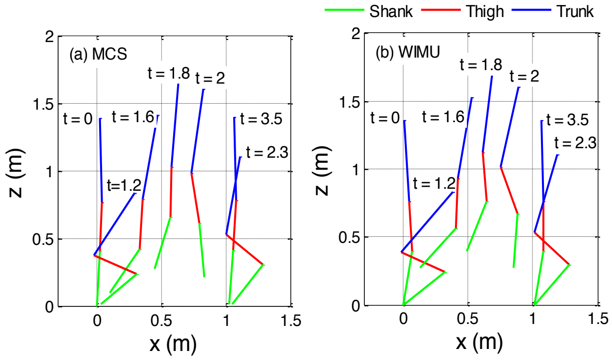

Fig.6 Stick picture of jumping motion measured by (a) motion capture system (MCS) and (b) proposed method (WIMU)

Table 1 Maximum displacement of hip joint

Trial No.	H_Z (m)			H_X (m)		
	MCS	WIMU	Error (%)	MCS	WIMU	Error (%)
1	0.274	0.367	34.0	0.97	1.029	6.1
2	0.271	0.351	29.1	0.888	0.737	-17.0
3	0.285	0.412	44.5	0.892	0.683	-23.5
4	0.267	0.297	11.3	0.922	0.867	-6.0
Ave.	0.274	0.357	29.8	0.918	0.829	-10.1

Table 2 RMS and error of RMS (RMSE) of joint angle between MCS and WIMU

Trial No.	θ_H (deg)		θ_K (deg)		θ_A (deg)	
	RMS (deg)	RMSE (%)	RMS (deg)	RMSE (%)	RMS (deg)	RMSE (%)
1	5.17	4.85	9.93	8.39	5.65	8.66
2	2.82	2.87	5.51	4.74	2.01	3.18
3	4.70	4.38	9.99	8.17	3.40	5.00
4	3.00	3.06	6.07	5.18	1.81	2.64
Ave.	3.92	3.79	7.87	6.61	3.22	4.87

contact all joint angles reached peak value around 2.23 s then returned to the standing posture. The maximum vertical displacement of hip joint from standing still obtained by MCS and WIMU are 0.274 m and 0.367 m, respectively and estimation error is 34.0 %. The horizontal displacement of hip joint by MCS and WIMU are 0.970 m and 1.029 m, respectively, and estimation error is 6.1 %. Fig. 6 compares the stick pictures of typical jumping motion in the sagittal plane. It is observed that the posture estimated by WIMU corresponds to that measured by MCS. Table 1 shows the displacement of jump performed four times. Although the vertical displacement estimated has error of 30 % on average and must be improved, qualitative changes are similar to the actual displacement. The error of the horizontal displacement is -10 % and shows good estimation relative to the vertical one. Table 2 shows RMS of θ_H, θ_K and θ_A between MCS and WIMU and error of RMS (RMSE) relative to the amplitude of each joint angle. All of averaged RMSE are smaller than 7 %. From the experimental results mentioned above, it is confirmed that the proposed method provides precise joint angles of lower body and qualitative estimation of displacement during standing long jump.

V. DISCUSSION

In this study the displacement of body in the air is calculated using acceleration and initial velocity of body center at heel off. The body acceleration based on the global coordinate system is affected by the FM of trunk which is updated using the angular velocity of trunk, meanwhile initial velocity results from the integration of angular velocity at trunk, thigh and shank. Therefore the angular velocity of trunk plays an important role for the precise estimation of displacement during jumping. Although the proposed model utilizes three rigid links, the trunk of human can be curved in any direction. This induces error in the position and the initial velocity of the body center. For example the vertical velocity is estimated smaller than actual one when the subject takes off while hunching his back. Mounting the WIMU for trunk near the hip joint will solve this problem and improve the accuracy of displacement of body in the air.

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