計測自動制御学会東北支部 第 309 回研究集会 (2017.6.23)
資料番号 309-5

慣性センサを用いた高速歩行時の歩行パラメータの測定

Estimation of gait parameter during high speed walking using Inertial sensors

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キーワード： 認知症の予兆 (Prediction of dementia)，最速歩行 (Fastest gait)，慣性センサ (Inertial sensor)，歩行解析 (Gait analysis)，歩行パラメータ (Gait parameter)

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1. Introduction

In recent years, relationship between motor function and risk of dementia were noticed[1–5]. Surveillance of walking condition is conducted as an indication of finding dementia symptoms and mild cognitive impairment[6]. The walking performance is evaluated using gait parameters such as walking speed and stride length.

Hirosaki University has conducted a health examination called Iwaki Project for approximately 1000 citizens of Hirosaki city since 2005. The aim of this project is to increase the health level of residents in Iwaki district and extend the average lifespan. 10 meter fastest walking examination was originally conducted to investigate the sign of dementia. Researches on gait analysis utilizing inertial sensor have been conducted in recent years[7–11]. Faculty of Science and Technology took part in the project from 2014 onwards and conducted 10 meter fastest walking examination to predict the sign of dementia and other diseases.

Optical three-dimensional motion measurement device is generally used for measurement of gait parameters, but it is unsuitable for large scale survey targeting multiple subjects. There are also problems such as limited measurement environment and preparation takes time. Meanwhile, Wearable Wireless Inertial Measurement Unit (WIMU) has been widely used for the quantitative evaluation of walking because it has been downsized and the measurement accuracy has been improved significantly. WIMU consists of a triaxial acceleration sensor and a triaxial gyroscope, and by using data obtained from these two sensors, the time change of the position and orientation of the WIMU is reconstructed into a three-dimensional space.

The authors have attempted to measure the gait parameters using the WIMU attached to the toe and succeeded in the measurement of general walking speed of about 2.8 [m/s][12]. However, when the walking speed goes as fast about 4 [m/s], desirable analysis results could not be obtained. This is because it is relatively easy to distinguish the gait cycle into swing phase and stance phase in general walking, but it is difficult to distinguish the gait cycle in high speed walking and it may exceed the measurement range of the sensor in some cases.

Conventional method uses inertial sensors with high sensitivity only and with sampling rate of 100 [Hz][13]. We found out that some subjects walk fast enough to exceed the measuring ranges of the older sensors and it is impossible to analyze their data properly. In this study, to solve this problem, inertial sensor system composed of low-sensitivity sensor in addition to high-sensitivity sensor is introduced. Sensor that operates at sampling rate 1 [kHz] is also introduced. Furthermore, we propose integration interval determination method of the gait cycle that can be applied to fast walking. Using the proposed method, we perform high speed walking experiment and examine the measurement accuracy. Moreover, gait parameters such as stride length, toe's height, and toe's angle are estimated from the measured walking motion and then compared with calculated results obtained from motion capture system.

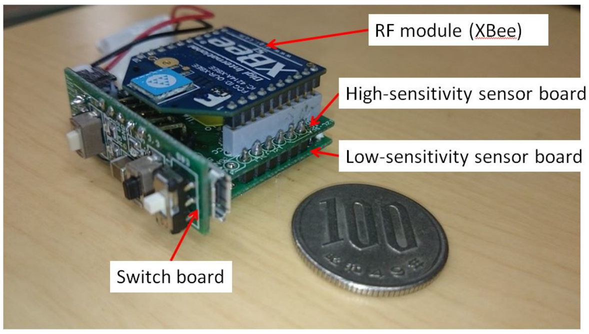

Fig. 1 WIMU without case (100yen coin for scale)

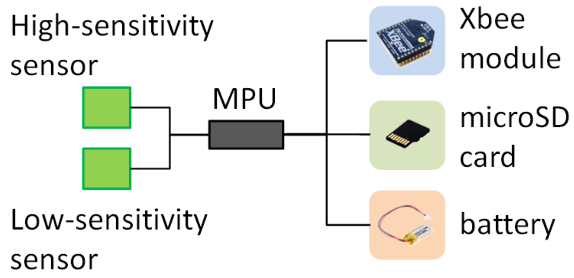

Fig. 2 Outline of the WIMU system

2. Measurement system

During fast motion, large acceleration and angular velocity occur. In this case, high-sensitivity sensors could not measure these values because they are over the measurement ranges. To overcome this problem, we introduced sensor which has wide measuring range in addition to sensor which has small measuring range. WIMU consists of two sensor boards; one mounts high-sensitivity acceleration sensor, high-sensitivity gyroscope, microprocessor unit, wireless communication module, and microSD card slot and the other board mounts low-sensitivity acceleration sensor and low-sensitivity gyroscope. Both boards are connected vertically to a switch board which consists of two controller switches, LEDs for information display, USB slot with charging function, and voltage regulator connected to lithium ion battery (Fig. 1). Table 1 shows the list of components used to build the WIMU. It consists of two kinds of sensors with different measurement ranges, sensor with small measurement range is called 'high-sensitivity sensor' and sensor with wide measurement range

Table 1 List of components

Component name	Pattern number	Manufacturer	Specification
MPU	dsPIC33FJ128GP802	Microchip Technology	28 pin
RF module	XBee	MaxStream	S1, S2
Acceleration sensor	MPU-6050	InvenSense Inc.	±16[g]
Gyro sensor			±2000[dps]
Acceleration sensor	ADXL375	Analog Devices Inc.	±200[g]
Gyro sensor	LPY4150AL	STMicroelectronics	±6000[dps]

is called 'low-sensitivity sensor'. Outline of the sensor system is shown in Fig. 2. Sampling frequency is set at 1 [kHz] to cope with extremely fast movement.

3. Theory

The gait parameters derived in this study are stride length, toe's height, and toe's angle shown in Fig. 3. A stride is an operation from the contact of the heel of one side of the foot to the next contact of the heel on the same side to the support surface and the distance is defined as stride length. Applying double integration to vertical acceleration, toe's height is obtained. There are generally two maximal values and one minimal value in the toe's height in one stride[14]. When the toe apart from the support surface, the first maximum point is reached immediately, during the swing phase. When the foot is swing forward, minimum point is reached and just before the foot lands on the support surface, second maximum point appears. In this study, during the swing phase, the two maximum points of the toe's height are defined as P_1 and P_3 and the minimum point is defined as P_2 as shown in Fig. 3. The toe's angle is amplitude of the angle of the toe direction from the floor and is defined by the difference between the maximum angle θ_{max} and the minimum angle θ_{min}.

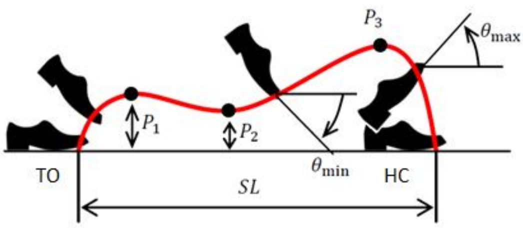

Fig. 3 Gait parameters investigated consist of toe's height, toe's angle, and stride length

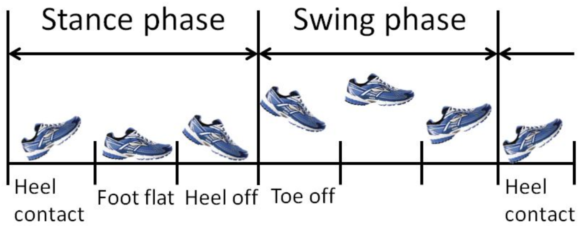

Fig. 4 The stance phase starts with heel contact (HC) and ends with heel off. Swing phase starts with toe off (TO) and ends with heel contact

A series of stride is called gait cycle and consists of stance phase and swing phase (Fig. 4). The stance phase refers to the period from the heel contact to the toe off and the foot is in contact with the support surface in this period. The swing phase refers to the time when the toe aparts from the ground until the next heel contact and the foot is away from the ground in this period.

Velocity is derived by integrating the acceleration data obtained from the sensor attached to the toe and further integration derives trajectory of the toe. In order to accurately estimate the moving distance, it is necessary to accurately distinguish the swing phase with the stance phase, and then to determine the integration interval. In this study, to determine the integration interval, we focus on the angular velocity in the dorsi-plantar-flexion direction of the foot (Fig. 5). Fig. 6 shows the relationship between the angular velocity in the dorsi-plantar-flexion direction of the foot and the movement of the foot. Point c_n in the figure is the minimum value of the angular velocity occurred when the foot is swing forward during the swing phase. Maximum point a_n of the angular velocity occurs before point c_n when the toe aparts from the support surface, and maximum point b_n of the angular velocity occurs after point c_n when the heel lands on the support surface. The integration interval is determined by including the maximum values of point a_n and point b_n.

The sensor system used in the conventional method used only high-sensitivity sensor. However in case of fast walking, the acceleration and the angular velocity exceed the measurement range of the high-sensitivity sensor used[15, 16]. In this case, the gait analysis accuracy decreases. Therefore, in this study, we attempt to cope with fast walking by introducing low-sensitivity sensor in addition to high-sensitivity sensor. Value exceeding the measurement range of high-sensitivity sensor is interpolated with the low-sensitivity sensor. Fig. 7 shows the procedure of interpolation of value exceeding measurement ranges. Acceleration threshold is set at ±100 [m/s^2] and angular velocity threshold is set at ±1000 [deg/s]. When the measured value of high-sensitivity sensor exceeds the threshold, the value is interpolated using the mea-

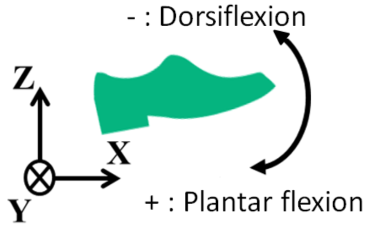

Fig. 5 Dorsiflexion is when the toe goes upward and the heel goes downward. Plantar flexion is when the toe goes downward and the heel goes upward

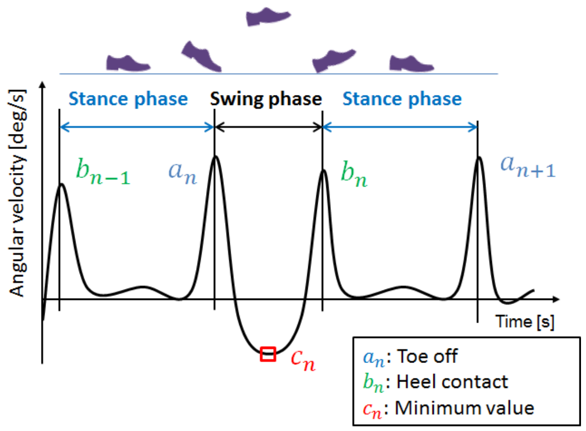

Fig. 6 The swing phase starts with toe off (TO) a_n and ends with heel contact (HC) b_n. In synthetic angular velocity waveform, maximal value is observed during TO and HC

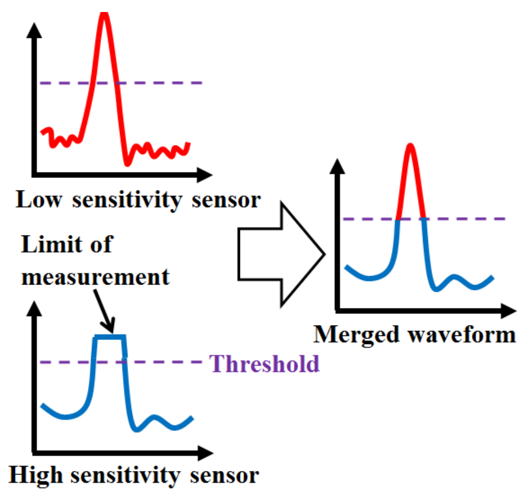

Fig. 7 When the measured value of the high sensitivity sensor exceeds the threshold, the measurement value of the low sensitivity sensor is used

sured value of low-sensitivity sensor.

4. Experiment

To evaluate the accuracy of the foot trajectory estimated using new sensor system and the new integration interval determination method, we asked 8 adult male participants aged 24.7 ± 7.5 years old to walk along a walkway at their fastest speed for 5 times. As shown in Fig. 8, WIMU is fixed on the tiptoe with vinyl tape, and acceleration and angular velocity information during gait are recorded. We simultaneously measured the position of the three markers attached to the WIMU using optical 3-dimensional Motion Capture System (MCS, Optitrack Prime 13, NaturalPoint Inc.) with six cameras placed on a side way focusing on a certain measurement volume as shown in Fig. 9. Fig. 10 shows schematic diagram of the entire experimental environment. The data of a stride, angle and trajectory of the right foot captured by MCS is used for reference. Motion-captured trajectory is considered as a reference foot trajectory and used for evaluation of estimation accuracy of sensor system. From the reference and estimated foot trajectories, gait parameters such as toe's height, toe's angle, and stride length are calculated and compared.

5. Results and discussion

5.1 Validity of sensor with sampling rate of 1 [kHz]

Fig. 11 shows the waveforms of synthetic angular velocity of sampling rate 100 [Hz] and 1 [kHz] plotted together. The horizontal axis represents time in second and the vertical axis represents the magnitude of synthetic angular velocity. The blue line is synthetic angular velocity waveform sampled at 100 [Hz] and the orange line is the synthetic angular velocity waveform sampled at 1 [kHz]. There are immeasurable data points in the waveform obtained by sensor with sampling rate of 100 [Hz]. Fig. 12 is the enlarged bottom right part of Fig. 11. The peak observable at 11 [s] in Fig. 11 is the heel contact. After the moment of the heel contact, there is vibration observed

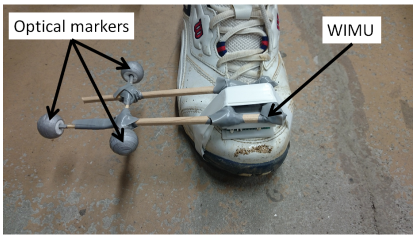

Fig. 8 WIMU with reflective markers mounted on shoe

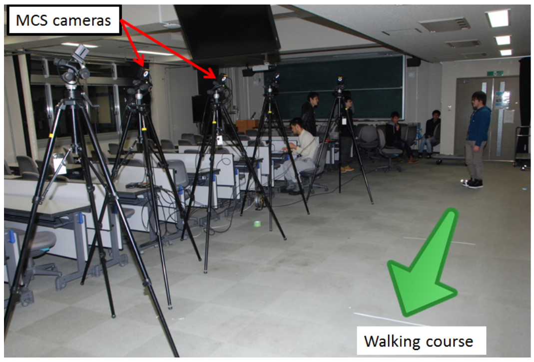

Fig. 9 MCS cameras are arranged on the right side of walking course

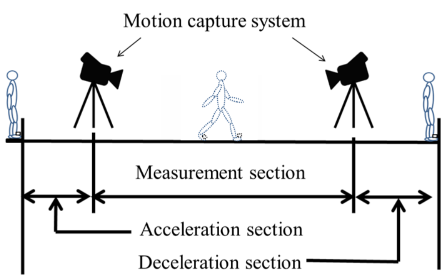

Fig. 10 Schematic diagram of gait experiment

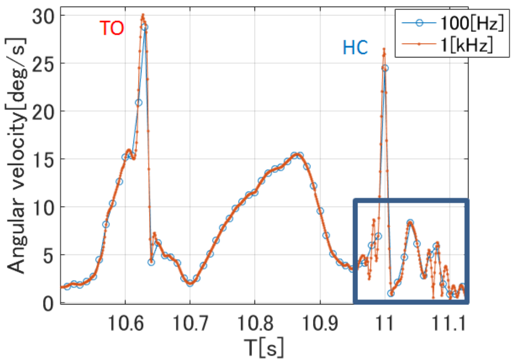

Fig. 11 Comparison of waveform between synthetic angular velocity measured with sampling rate 100 [Hz] and those measured with sampling rate 1 [kHz]

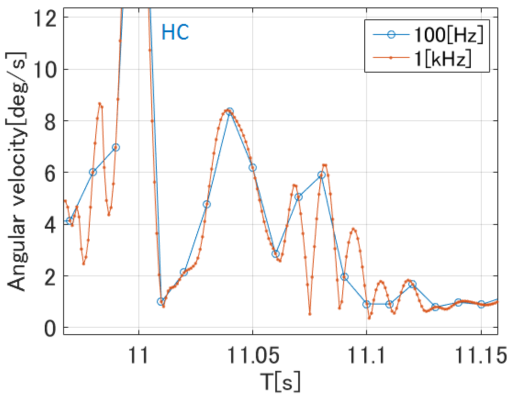

Fig. 12 More data can be observed when sampling rate of sensor is set to 1 [kHz] compare to those set at 100 [Hz]

in the 1 [kHz] sampling rate waveform but unclear in the 100 [Hz] sampling rate waveform.

Estimation results of gait parameters for sampling frequency 100 [Hz] and 1 [kHz] are compared. Fig. 13 shows the comparison of toe's height. Estimation error drops for P_2, and P_3 but increase for P_1 when sampling rate 1 [kHz] is applied. Fig. 14 and Fig. 15 show the estimation error for angle amplitude and stride length respectively. Error became slightly smaller in angle amplitude estimation. However for stride length, estimation precision significantly improved. These results shows that in order to

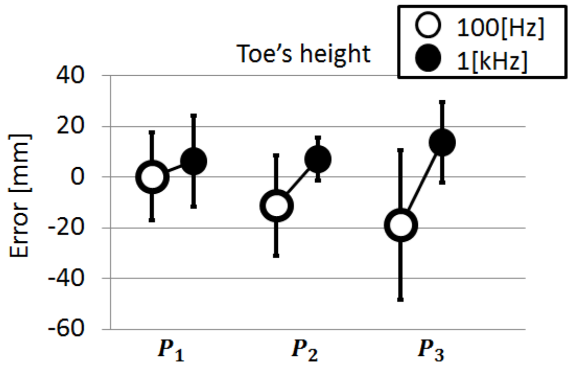

Fig. 13 Estimation error of toe's height

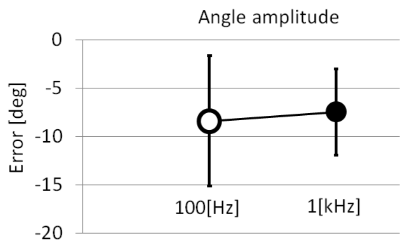

Fig. 14 Estimation error of angle amplitude

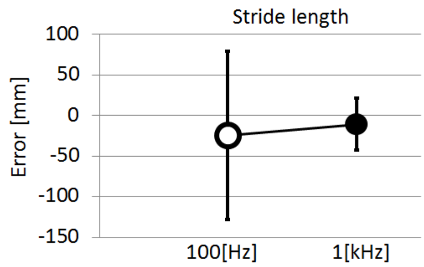

Fig. 15 Estimation error of stride length

estimate the gait parameters precisely, the utilization of sensor with sampling rate of 1 [kHz] is necessary.

5.2 Comparison of gait parameters

There are a total of 40 samples (8 subjects × 5 trials). Within that, there are 12 toe's height waveforms of WIMU or MCS which do not have P_1 and P_2. In this case, since the angle amplitude and stride length calculated from these data are reliable, only the toe's height data is excluded from accuracy comparison. Thus, there are 28 data of toe's height, 40 data

Table 2 Error in estimation of gait parameters

Parameters	Average error	
	100 [Hz]	1 [kHz]
Toe's height		
P_1	0.22±17 [mm]	6.23±17 [mm]
P_2	-11.18±19 [mm]	7.10±8 [mm]
P_3	-18.77±29 [mm]	13.72±15 [mm]
Toe's angle amplitude	-8.42±6 [deg]	-7.46±4 [deg]
Stride length	-24.15±103 [mm]	-10.64±32 [mm]

of toe's angle amplitude, and 40 data of stride length. Table 2 shows the estimation error of each parameters for sampling rate 100 [Hz] and 1 [kHz]. Estimation of toe's height has low accuracy entirely. The method of choosing the integral section plays important role in determining the accuracy of estimation of toe's height. Each person has different characteristic of gait and finding a new algorithm which can cope more type of gait will be our task in the future. Estimation of amplitude of toe's angle has considerably high accuracy with error of -7.46 [deg]. The estimation accuracy of stride length shows the highest accuracy with error of -10.64 [mm].

6. Conclusion

In this study, we developed new toe-mounted inertial sensor with integration interval determination method that can correspond to fast walking. The inertial sensor unit is consisting of high-sensitivity sensor with small measuring range and low-sensitivity sensor with large measuring range. The interpolation method between the values of high-sensitivity sensor and low-sensitivity sensor was introduced and the validity of WIMU with sampling rate of 1[kHz] was also investigated. We conducted gait experiments using the developed method and examined the measurement accuracy. Using this new WIMU system, the accuracy of foot trajectory was evaluated by comparing the gait parameters with data calculated from MCS. The results of high speed walking analysis were as follows. The estimation of toe's angle amplitude and stride length is proved to be of high accuracy. However, the estimation of toe's height still needs improvement. We also confirmed that the method of interpolating values exceeding the measurement range of high-sensitivity sensor by introducing low-sensitivity sensor is effective for the analysis of fastest walking. Using WIMU with higher sampling rate improves the measurement of characteristics of high speed walking.

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