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A Trial of Making Reference Gait Data for Simple Gait Evaluation System with Wireless Inertial Sensors

Yuta Karasawa, *Student Member, IEEE,* Yuta Teruyama, *Student Member, IEEE,* Takashi Watanabe, *Member, IEEE*

***Abstract*—Recently, the use of wearable inertial sensors have been widely studied in the field of human movement analysis. Our research group developed a wearable motion measurement system using the wireless inertial sensors for rehabilitation training and daily exercise. However, there are few reference data to evaluate motor function. In this paper, reference data of joint and inclination angles of lower limb and that of gait event timing for gait evaluation were made by measurement with 4 healthy subjects in their twenties. Average values of inclination and joint angles and gait event timings were similar to those seen in literature. These suggest that the averaged data obtained in this paper can be used as reference data. Then, gait data of a healthy subject in his thirties were compared with the reference data. Most of angles and all the gait event timings were considered to be standard of 20's. However, some angles of the healthy subject in his thirties were considered not to be the standard partly. These differences in evaluation were considered to depend on a level of similarity of movement to the reference data. It was expected to evaluate the level of similarity of movement from various parameters.**

I. Introduction

In the rehabilitation, evaluation of motor function of patients is important. Physical therapists evaluate a level of motor function from visual information, manually measured angles, and so on. However, those evaluations may depend on his or her experience. Therefore, it is expected that the objective evaluation based on quantitative data allows more effective rehabilitation.

For the measurement of movements, optical 3D motion analysis system, electronic goniometers, force plates, and so on are commonly used in research work. However, these systems have some shortcomings that the measurement condition is limited in place and space, and costs of these systems are very high and so on.

Recently, inertial sensors such as accelerometers and gyroscopes have been used in measurement and analysis of human movements because of their shrinking in size and cost. Many studies using inertial sensors in detecting gait event [1, 2], measurement of joint angle or segment tilt angle [3–5] and stride length [6, 7] have been performed.

In our previous study, wearable motion measurement system using wireless inertial sensors was developed for simple gait evaluation [8]. However, there are few reference data measured by wireless inertial sensors to evaluate motor function from measured data. For example, by comparing patient's gait data to average data of healthy people, it is thought that gait of patient can be evaluated objectively. In this case, the average data can be a set of reference data.

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Yuta Karasawa, Yuta Teruyama and Takashi Watanabe are Grad. School of Biomed. Eng., Tohoku University, Sendai, Japan (e-mail: {yuta.karasawa, yuta.teruyama, nabet}@bme.tohoku.ac.jp).

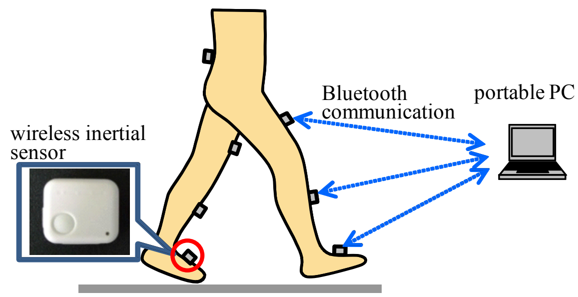


Fig.1 Outline of the wearable sensor system used in this study.

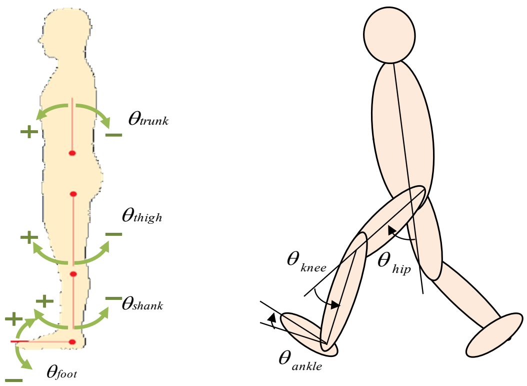
Questions focused in this study are whether average values can be used as reference data or not and how the reference data are used in gait evaluation. Therefore, the purposes of this paper are to make reference data for males in their twenties by measuring gait of healthy subjects in their twenties and to show usefulness of the reference data in finding similarities and differences of gait movement. Then, the reference data in their twenties were compared with gait data of a healthy male in his thirties for considering how the reference data are used in gait evaluation.

II. Making of Reference Gait Data

A. Measurement Method

The wearable motion measurement system consists of seven wireless inertial sensors (WAA-010, 39 × 44 × 12mm , Wireless Technologies) and a portable PC (Fig. 1). The wireless inertial sensor includes a 3-axis accelerometer (AXDL345, Analog Devices) and 3-axis gyroscope (IDG-3200, Inven Sense). The sensors are fixed on the feet, the shanks and the thighs of both legs, and lumbar region with stretching bands. The sensors are put inside of pocket of the band. Acceleration and angular velocity signals of each sensor are measured with a sampling frequency of 100Hz, and are transmitted to PC via Bluetooth network. Measurement, recording, and joint angle calculation were implemented in LabVIEW (National Instruments).

In this paper, reference data for males in their twenties were made. Measurements of joint and inclination angles were conducted on 4 healthy subjects (male, and 22-23 years old). The subjects were asked to walk 15m on level ground at normal walking speed (usual comfortable speed chosen by the subjects). Six trials were performed with each subject.



(a) Inclination angles (b) Joint angles

Fig.2 Definition of inclination and joint angles

B. Data Analysis

The first two trials and the first two gait cycles and the last two gait cycles in each trial were removed from analysis to evaluate steady state walking. From the data of the inertial sensors, joint angles and inclination angles of body segments were calculated by the method based on the Kalman filter [8]. Figure 2 shows the definition of inclination and joint angles. In Fig. 2, θ_{hip}, θ_{knee} and θ_{ankle} show joint angles. θ_{trunk}, θ_{thigh}, θ_{shank} and θ_{foot} show inclination angles. The joint angles were calculated by the followings:

$$\theta_{\text{hip}} = \theta_{\text{trunk}} + \theta_{\text{thigh}} \quad (1)$$

$$\theta_{\text{knee}} = \theta_{\text{thigh}} - \theta_{\text{shank}} \quad (2)$$

$$\theta_{\text{ankle}} = \theta_{\text{foot}} - \theta_{\text{shank}} \quad (3)$$

Time to the foot flat (FF), the heel off (HO), and the toe off (TO) from the heel contact (HC) were also calculated. The FF, the HO, and the TO were detected by threshold of angular velocity measured with the sensor attached to the foot. The HC was detected by threshold of acceleration measured with the sensor attached to the shank after detection of the TO.

First, each gait cycle was detected by the HC point. Then, time of the gait cycle was normalized. After that, average angle wave patterns and average gait event timings of each subject were calculated. Finally, the average values of those of all subjects were calculated. In this paper, these average data were defined as reference data for males in their twenties.

C. Reference data of Angle Wave Pattern

Figure 3 shows average angle wave pattern of each part. Average wave patterns of hip, knee, ankle joint angles, shank inclination angle and these standard deviations (SD) were similar to plots pattern of literature [9].

Table I shows the average values of standard deviation of average angle wave pattern and the maximal values of that in one gait cycle to evaluate difference in variability of angle wave pattern between parts. The average values of SD were approximately 3-6 deg. On the other hand, the maximal values of the SD were approximately 5-13 deg. Values of SD varied in a gait cycle, especially ankle joint angle and foot inclination angle. In these parts, the point of maximal values of SD was just before the timing of the TO shown in the following subsection.

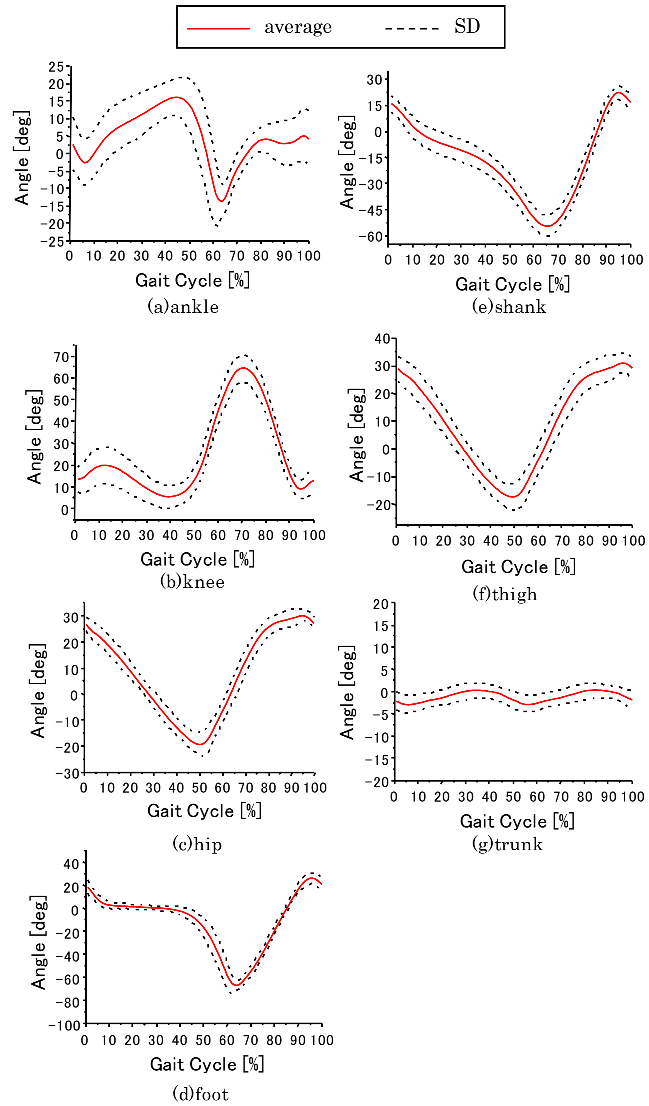


Fig.3 Average patterns of joint angles and inclination angles. 0 and 100 in the x-axis are the heel contact.

TABLE I. AVERAGE AND MAXIMAL VALUES OF STANDARD DEVIATION OF AVERAGE ANGLE WAVE PATTERN

	average values of SD (deg)	maximal values of SD (deg)	point of gait cycle when SD value is maximal (%)
ankle	6.2	11.3	57
knee	6.2	8.4	15
hip	3.6	5.0	53
foot	4.7	13.0	57
shank	5.7	6.5	25
thigh	4.8	6.2	65
trunk	1.8	2.0	50

D. Reference data of Gait Event Timing

Figure 4 shows average gait event timings calculated from results of 4 trials of 4 subjects. The timing of the FF was about 10 percent of a gait cycle, the timing of the HO was about 40

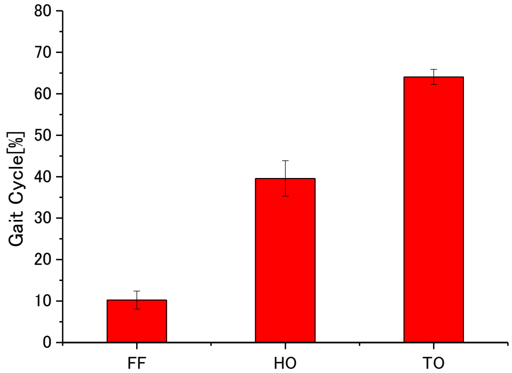


Fig.4 Average gait event timing of 4 subjects. 0 of vertical axis is heel contact.

percent of a gait cycle, and the timing of the TO was about 65 percent of a gait cycle. On the other hand, according to the previous study [10], the timing of the FF was about 10 percent of a gait cycle, the timing of the HO was about 40 percent of a gait cycle, and the timing of the TO was about 60 percent of a gait cycle. Gait event timings in this paper did not have large difference in comparison with the previous study.

III. An Application Test

It is necessary to consider how to evaluate motor function of patients based on the reference data. Since the reference data are average values of the data of plural subjects, variability between subjects appears in form of the standard deviation. Therefore, as an example, if patient's angle wave patterns were in the range of standard deviation of reference data, his or her gait can be considered to be standard gait. In this paper, standard deviation was used as the criteria to determine whether subject's gait is standard gait or not as a trial of gait evaluation.

Here, as an example of evaluating movement, gait data of a healthy subject in his thirties was evaluated whether his gait can be considered to be standard gait of 20's or not by comparing to the reference data.

A. Angle Wave Pattern

Figure 5 shows angle wave patterns of the reference data obtained in this paper and gait pattern of a healthy male subject in his thirties. In ankle, hip joint angles and thigh inclination angle, some points were not in the range of standard deviation of the reference data. For ankle joint angle, the points that were not in the range of standard deviation were near the timing of the TO. In hip joint angle and thigh inclination angle, the points that were off from the range of the standard deviation were near the timing of the HC.

Root mean squared error (RMSE) and correlation coefficient (CC) between the reference data and data of the healthy subject in his thirties were calculated (RMSE-30's, CC-30's). In addition, average values of the CC and RMSE between the reference data and subjects in their twenties were also calculated (RMSE-20's, CC-20's). They are shown in Figure 6. Values of CC-30's were larger than those of CC-20's, excepting the hip joint angle and the thigh

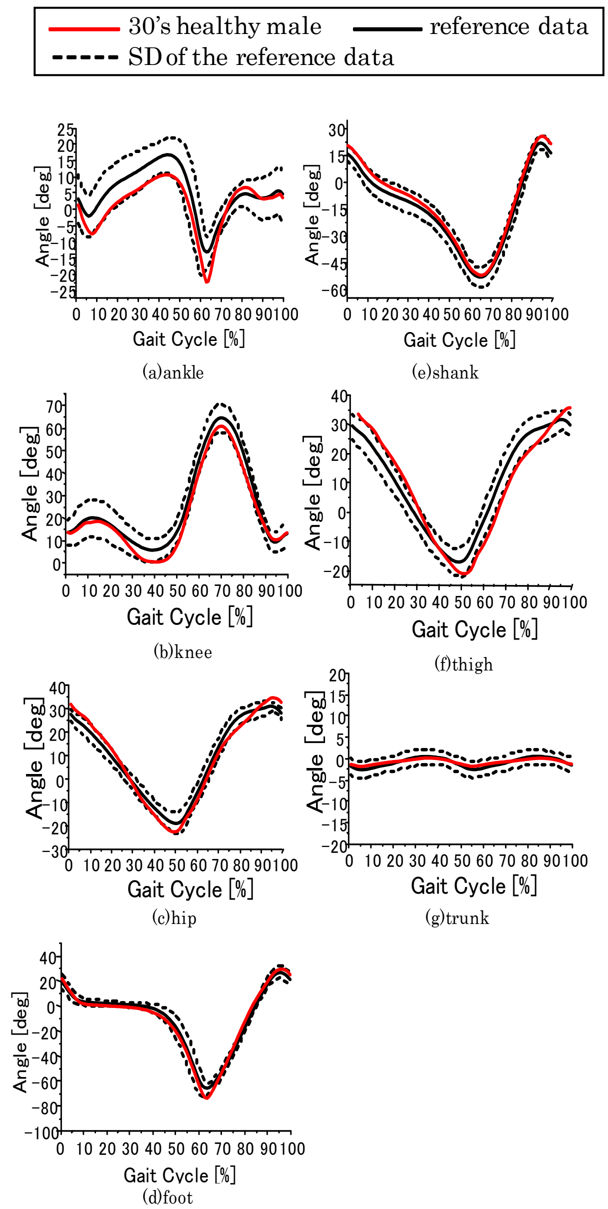


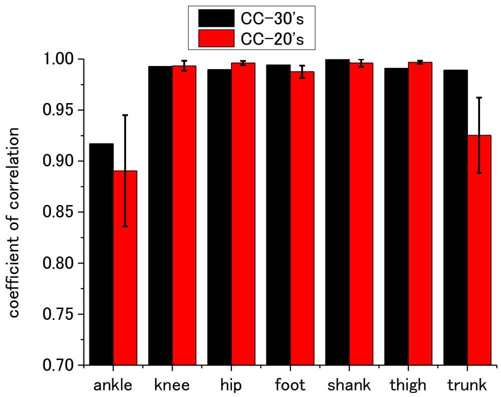
Fig.5 Results of the comparing average wave patterns of joint and inclination angles of a healthy subject in his thirties with those of the reference data.

inclination angle. On the other hand, the values of RMSE-30's were smaller than values of RMSE-20's for all inclination and joint angles.

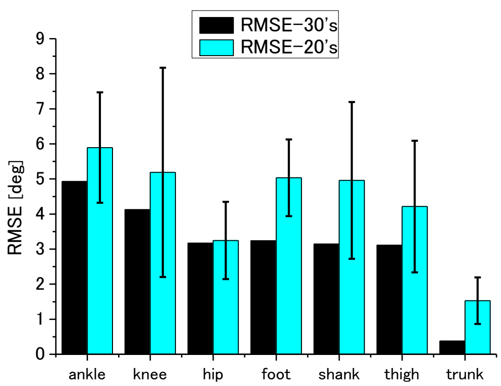
From above results, joint angle and inclination angles of the subject in his thirties can be considered to be standard of 20's excepting the ankle, hip joint angle and the thigh inclination angle.

B. Gait Event Timing

Figure 7 shows gait event timing of the reference data and that of the subject in his thirties. The average values of gait timing of the subject in his thirties were within standard deviation of the reference data. Therefore, it is considered that the gait event timing of the healthy subject in his thirties is standard of 20's.



(a) correlation coefficient



(b) RMSE

Fig.6 Comparing CC and RMSE values between the reference data and the healthy subject in his thirties with average values of the CC and RMSE between the reference data and each 4 subject in their twenties.

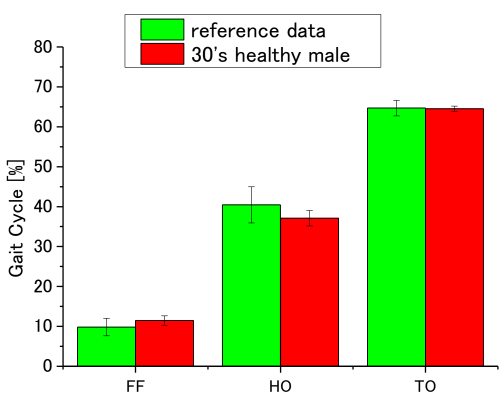


Fig.7 Results of comparing gait event timings of subject in his thirties with that of the reference data.

IV. Discussion

From the measurement results of gait of healthy subjects in their twenties, reference gait data for males in their twenties were made for evaluations of gait using the wearable motion measurement system. Average values of inclination and joint angles were similar to plotted pattern seen in literature [9]. The standard deviations of the average angle patterns were also similar to the previous study. In addition, gait event timings in this paper did not have large difference in comparison with the previous study [10]. These suggest that the averaged data obtained in this paper can be used as reference data. However, it is necessary to increase the number of subjects to collect data for making reference data. It is also necessary to collect data from many subjects of various age groups. In addition, it is considered that the reference data depending on a walking speed is useful, since the patient's walking speed tend to be slow. Reference data are required to be compared under different walking speeds.

Gait movement of a healthy subject in his thirties was evaluated by comparing to the reference data for males in their twenties. The results suggest that the most of gait data of the healthy subject in his thirties were considered to be standard of 20's. For ankle joint angle, the points that were not in the range of standard deviation were near the timing of the TO. As shown in TABLE 1, standard deviation of ankle joint angle was large near the timing of the TO. Therefore, when angle wave pattern of ankle joint angle is evaluated, it is necessary to take into account the fact that variation of movement was large near the timing of the TO. For hip joint angle and thigh inclination angle, it can be considered not to be the standard because values of CC-30's were smaller than CC-20's and differences in angle wave pattern were partly found. On the other hand, it can be considered to be the standard because RMSE-30's were lower than RMSE-20's. These differences in evaluation are considered to depend on a level of similarity of movement. It is expected to evaluate level of similarity of movement from various parameters as shown in this paper.

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