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Validation of Potential Reference Measure for Indoor Walking Distance to Evaluate Wearable Sensing Devices*

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Abstract— **The walking distance estimated from the coordinate position information of the center of mass obtained via Xsens MTw Awinda were validated from 5 adult volunteers and the accuracy was shown significantly high. (Average absolute error of -1.22% with a standard deviation of 2.26%)**

Clinical Relevance— **Wearable devices has been expected to measure stride length, which may be referred to as a sign of various diseases such as muscle fatigue, onset of frailty, and dementia. In order to determine the appropriate wearable device to be used, Xsens MTw Awinda can be best suited to evaluate the accuracy.**

I. Introduction

Gait is a good indicator of a person's health condition. Recent studies have shown that daily stride length correlates with muscle mass [1] and can be the identifier to determine signs of muscle fatigue in athletes [2], frailty symptoms in the elderly [3, 4], and early signs of dementia [5]. The number of steps is also used as a measure of activity for calculating calorie consumption in a wide range of healthcare solutions, and it is believed that walking about 10,000 steps a day can help prevent chronic diseases such as obesity. Although, recent study has mentioned that the number of steps alone does not accurately capture a person's activity level, and that it is necessary to use walking speed as an indicator of activity level [6]. This is because the actual energy consumption of a person walking slowly may differ from that of a person walking at a high intensity because of the difference in exercise intensity.

In recent years, there seem to be several evaluation studies on the accuracy of measuring the number of steps using wearable devices, but there are few evaluation studies on walking speed and stride length information using wearable devices. If the device is said to be able to measure the number of steps accurately, as long as the measurement of walking distance can be evaluated, the stride length can be obtained by dividing the walking distance by the number of steps, and the walking speed can be obtained by dividing the walking distance by the time required. Therefore, it can be said that a wearable device can evaluate behavioral information to some extent if it evaluates the accuracy of the number of steps and walking distance at least.

Then, the problem is how to appropriately evaluate the accuracy of measurement of walking distance. In the conventional research, the subject walks on a treadmill with the speed set to a certain level, and the evaluation is made by comparing the walking distance and walking speed calculated via the wearable device built-in inertial sensor with the set value of the walking speed and the measured walking distance output from the treadmill [7]. However, the inertial sensor does not provide any information about the walking speed. However, this evaluation method is not appropriate because the data collected by the inertial sensor differs between the data collected during walking motion at a fixed point, such as on a treadmill, and the data collected during normal walking motion in which the latitude and longitude coordinates change. As a result, the walking speed estimation model obtained using this evaluation method is an algorithm that focuses on the periodic information extracted from the inertial sensor signals, and not an algorithm obtained from the feature information that takes into account the actual distance traveled. On the other hand, if we use the evaluation method based on GPS coordinate data, it is possible to create an algorithm that focuses on the feature information for the distance traveled [8]. However, there are two problems with GPS coordinate data. The first is the measurement accuracy of the coordinate information. Depending on the environment and equipment used, the latitude and longitude information of each measurement point can vary from a few meters to several hundred meters. Of course, it is possible to track the average trajectory of walking by using Kalman filter, etc., but it is insufficient as reference data for the distance traveled, taking into account detailed movements such as the swinging of the center of gravity in the left-right direction during walking. Secondly, it is limited to linear walking outdoors only, and it is obvious that GPS sensors cannot read the earth axis information accurately indoors or underground. In addition, it is extremely difficult to grasp the distance traveled by a walking motion in a small space such as in a room. Considering these problems, we think it is very important to consider the choice of equipment that can be used for the evaluation of wearable devices and which can accurately calculate the distance information even for small walking movements indoors or outdoors. In this study, we hypothesize that it is appropriate to use Xsens MTw Awinda, which is used in sports, medicine, video production, etc., as the equipment, and consider how accurate it is.

II. Method

A. Participants

Participants were recruited from the staff of the Research and Development Department of Arblet Inc. The study was conducted in the spirit of the Declaration of Helsinki (revised in October 2013) and in accordance with the Ethical Guidelines for Medical Research Involving Human Subjects (partially revised on February 28, 2009 by the Japanese

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Five subjects are enrolled in the study. Table 1 shows the characteristics of the 5 study participants from whom the data were successfully collected. Their mean age was 35.6 with a standard deviation of 8.24.

TABLE I. PARTICIPANT CHARACTERISTICS

Demographic features		Count (%)
Age Group	20 - 29 years	1 (20%)
	30 - 49 years	3 (60%)
	50 - 59 years	1 (20%)
Sex	Male	3 (60%)
	Female	2 (40%)

B. Devices

The devices used in this study included the Xsens MTw Awinda from Xsens Technologies B.V. (Enschede, Netherlands), and SVAJ003 from Seiko (Tokyo Japan).

The Xsens MTw Awinda enables the Awinda radio protocol which ensures time-synchronication better than 10µs between MTw on a wireless body area network. The Xsens MTw Awinda was set to have a sampling rate of 60Hz during this study. SVAJ003 is the standard stopwatch which can track one hundredth of a second and has a functionality to record the lap time. The SVAJ003 was set to be the running lap time recording mode during this study.

C. Study Design and Data Collection

Each enrolled participant was measured for 11 body dimensions before starting the measurement: the (1) Body Height, the (2) Foot Length, the (3) Shoulder Height, the (4) Shoulder Width, the (5) Elbow Span, the (6) Wrist Span, the (7) Arm Span, the (8) Hip Height, the (9) Hip Width, the (10) Knee Height, and the (11) Ankle Height. These measurements were taken at least five times per subject with a measuring tape, and the average values were used as input values for the Xsens MTx Awinda measurement system, Xsens MVN2020.2. For the areas where left-right differences were expected, the measurements were taken three times for each side, and the average value was used. After taking the measurements, the subject attaches the 17 sensors to each of the areas circled in Figure 1.

Figure 1. Experimental Setup. The Xsens MTx Awinda were placed at 17 different area on the participant body.

After the participants were ready to start for measurement experiment, they were asked to stand upright at the start line of the 400m running track so that their toes would not stick out and walk when the signal to start measurement was given. In order to receive the sensor data sent from Xsens MTw Awinda via ZIGBEE communication, the measurer walked alongside the subject with a laptop PC connected to the ZIGBEE receiver, not more than 3m away. Each time the subject passed the passage points marked on the 400m track (90m, 190m, 290m, 390m), the lap time was measured with a stopwatch, and the final lap time was measured at the timing when the 400m walk was completed. These passing points were the lines where the runners waiting for the baton in the 4 x 100 m relay race.

The subjects walked five laps of the 400 m track at three different walking speeds, the normal speed, faster speed, and slower speed, for a total of 15 laps. Since it is difficult to control the walking speed in outdoor walking measurement unlike on a treadmill, we first asked the subjects to walk one lap of the 400m track at their own comfortable walking speed, and then asked them to walk at the same speed, faster speed, and slower speed.

D. Data Treatment

The Xsens MTw Awinda use its proprietary algorithm to calculate the position, velocity, acceleration of the center of mass on the respective records. The Xsens MVN2020.2 was used to processed at four different configuration combinations and export those data regarding the subjects' center of mass during the walking experiment.

E. Data Analysis

Based on the recorded lap times, the subjects' walking speed at each corner were calculated, and the variations in walking speed obtained in this study were checked.

The data obtained from Xsens MTw Awinda was used to calculate the norm velocity of the center of mass on the plane paralleled to the surface of the Earth as shown in Equation 1.

$$v_{norm,t} = \sqrt{{v_{x,t}}^2 + {v_{y,t}}^2} \quad (1)$$

For each window frame of 0.1 second with 50% overlap, linear regression is performed, and the peaks of the change in velocity was tracked. The point where the first peak is detected is set as the time to start walking, and the point where the time change information is 0 seconds, measured using the stopwatch. For the elapsed time at each measurement point, the cumulative walking distance from the start of walking was calculated, and the difference from the reference distance information was evaluated.

III. RESULT

Figure 2 shows the box plot of the measured velocity distribution of each of the five subjects as they walked at three different intentional walking speeds. As shown in the figure, the subjects measured walking speed data ranging from a minimum of 0.92 m/s to a maximum of 1.95 m/s. The figure also shows that a wide range of walking speed data was measured for each subject.

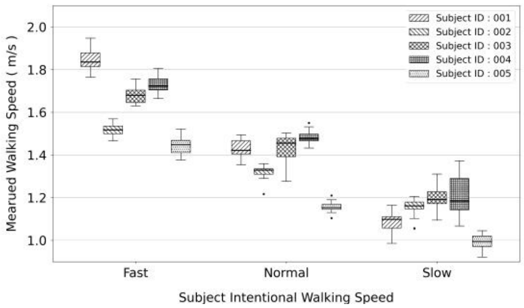

Figure 2. Box plot of the Subject Intentional Walking Speed vs. Measured Walking Speed.

The coordinate position, velocity, and acceleration information of the center of mass were used to calculate the walking distance. For the coordinate position, the walking distance between frames was calculated using the x and y coordinate positions of two consecutive frames using the Equation (2), and the total walking distance was calculated according to the time elapsed from the starting point.

$$\Delta d_t = \sqrt{(x_t - x_{t-1})^2 + (y_t - y_{t-1})^2} \quad (2)$$

The velocity of the center of mass along the x and y coordinate, v_x and v_y , were used to calculate the norm velocity along the x-y plane as shown in Equation (1). The walking distance in the relation to the elapsed time was obtained by integrating the norm velocity on the x-y plane according to the Trapezoidal Rule [9] as shown in Equation (3).

$$\int_a^b f(x)dx \approx (b-a)\frac{f(a)+f(b)}{2} \quad (3)$$

The acceleration of the center of mass along the x and y axes, a_x and a_y, were used to calculate the velocity along the x and y axes, v_x and v_y, by integrating a_x and a_y in respect to the elapsed time according to the Trapezoidal Rule as shown in Equation (3). The walking distance in the relation to the elapsed time was obtained via the same procedure as the walking distance achieved from the velocity of the center of mass along the x and y axes.

TABLE II. PERCENTAGE ERROR OF ESTIMATED WALKING DISTANCE

Source Signal	Percentage Error (+/- STD)
Center of Mass - Position	-1.22% (+/- 2.26%)
Center of Mass - Velocity	-0.81% (+/- 13.16%)
Center of Mass - Accelerometer	367.55% (+/- 1307.91%)

As shown in Table 2, the walking distances calculated in from each source signals were compared against the actual walking distance. The accuracy of the estimated walking distance using the acceleration of the center of mass by second-order integration was significantly lower among all. Although there was only a 0.4% difference in the mean error of the estimated walking distance calculated from the velocity and coordinate position of the center of mass, there is more than a 10% difference in the standard deviation. This indicates that the proprietary processing algorithm provided in Xsens MVN 2020.2 accurately track the coordinate positions of center of the mass using methods such as Dead Reckoning.

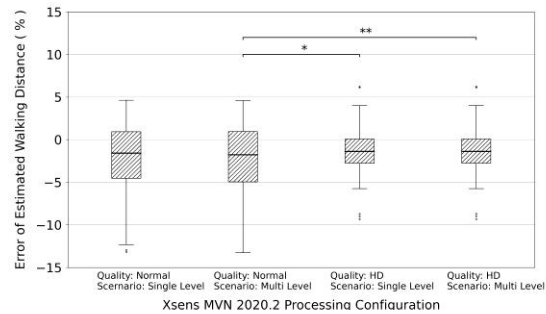

Figure 3. Box plot of the Error of Estimated Walking Distance for All possible Reprocessing Configuration available at Xsens MVN 2020.2.

Having found that the accuracy of the calculation of the walking distance using the coordinate position of the center of mass is relatively good, the variation among the different Xsens MVN 2020.2 processing configuration was examined. As shown in Figure 3, the error tends to be smaller when the processing configuration is [Quality: HD, Scenario: Single Level] or [Quality: HD, Scenario: Multi Level] than when the setting is [Quality: Normal, Scenario: Multi Level]. Although statistical tests indicate that there is no significant difference due to the fact that the p-value is less than 0.05 since the p-value calculated when comparing [Quality: Normal, Scenario: Single Level] with [Quality: HD, Scenario: Single Level] and [Quality: HD, Scenario: Multi Level] was 0.06, the graph seems to indicate some difference under those different processing configurations and the data should seem to be further investigated [10].

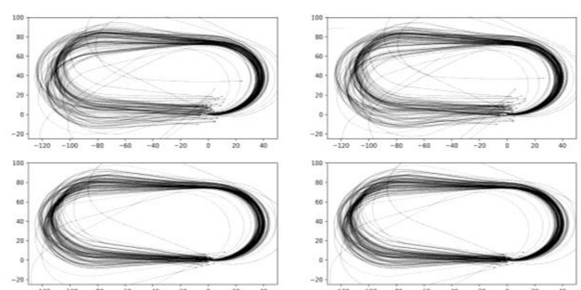

Figure 4. Scatter plot of the Center of Mass x / y coordinate position where the starting position is located at coordinate (0, 0). (Top-left) Normal / Single Level, (Top-right) Normal / Multi Level, (Bottom-left) HD / Single Level, (Bottom-right) HD / Multi Level

As shown in Figure 4, the data processed with Quality set to HD, the subjects were returning to the close position to the starting point (0, 0) after 400m of walking compared to the data processed with Quality set to Normal. Even if there is no statistically significant difference, it is recommended to set the process Quality to HD. In this study, the subjects walked on a 400m track, which is a flat surface with no height difference, so there was no significant difference between the different Scenario configurations, Single or Multi. However, it may be necessary to re-evaluate the results by changing the environment of the measurement experiment, such as adding height differences to the walking course.

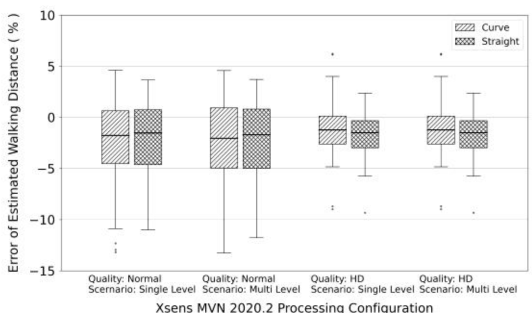

Figure 5. Box plot of the Error of Estimated Walking Distance for All possible Reprocessing Configuration available at Xsens MVN 2020.2 while separately evaluating straight line walking and curved line walking.

According to the results shown so far, it was found that the walking distance can be accurately extracted by calculating the walking distance using the coordinate information of the center of gravity after applying the process with the quality set to HD in Xsens MVN 2020.2. Furthermore, as shown in Figure 5, there was no significant difference in the estimated walking distance between walking on a straight line and on a curved line. This indicates that the process algorithm does not include any process that gives an advantage to a specifically biased walking motion.

IV. DISCUSSION

As shown in this study, the accuracy of the estimated walking distance is extremely high, with an average absolute error of -1.22% (+/- 2.26) per 90-110m of measured distance. In practices, it takes time and effort to measure the subject's skeletal information accurately and to make sure that the sensor is firmly fixed to the appropriate part of the body when it is worn, but it is possible to measure without being in an enclosed space surrounded by optical sensors in all directions, as is the case with full-body motion tracking technology that uses optical sensing. In addition, the fact that the error is only about 1 meter when converted into actual measurement values means that this equipment can measure values with much better performance than distance data using GPS.

Indeed, it is important to confirm that there is no loss or abnormality in the measurement data when the measurement experiment is conducted under free movement, whether indoor or outdoor. In addition, since the measurement device uses ZIGBEE communication, it is necessary to ensure that the communication distance between the device and the communicating PC is not too far apart, and that the 2.4 GHz bandwidth used for ZIGBEE communication is not interfered with. As long as these concerns are taken care of, the Xsens MTw Awinda can be used as an accurate measurement device for clinical research requiring free-living gait information, which the past studies had difficulties in collecting such information due to the lack of reference equipment.

Some may consider a simple gate system as an alternative for indoor validation of walking distance/velocity. Of course, if the goal is to collect data on walking in a straight line, this method will have some value. However, if the purpose of using a wearable device is to collect behavioral information in daily life, it is very important to build a setup that can serve as a reference for walking information in an environment that is as close to daily life as possible.

In conclusion, when implementing a function to measure walking distance in many wearable devices including wrist-worn type, it is recommended to evaluate the accuracy by comparing it with the walking distance calculated from the center of mass coordinate position information obtained via using Xsens MVN Awinda. The main reason for this is that it is difficult to compare the accuracy of measurements on a treadmill or GPS against the actual measured walking distance under free-living motion. This study has shown the potential for the informed use of the Xsens MTw Awinda as a reference measurement in future gaits studies using wearable devices.

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