IMU-based Smart Knee Pad for Walking Distance and Stride Count Measurement

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***Abstract*—To calculate the knee angle, stride counts, and walking distance, we propose a system, iKneePad, fusing two 9-axis sensors with Bluetooth equipped on the thigh and shank segments. The changing rates of hip and knee angles are used to determine the beginning and the ending of a stride. The thigh length, shank length, hip angle, and knee angle are used to calculate the walking distance. The experimental results show that the accuracy of stride count is 100%, the absolute mean errors of knee angle are 2.99° and 1.42° for the maximum and minimum flexion angles, respectively. For walking distance, the mean error rates are -2.40% and -2.26% for short (10m) and long (33m) distances, respectively. The proposed system also instantly provides feedback to users by showing on an Android smartphone when conducting rehabilitation or exercise with iKneePad.**

I. Introduction

Walking is a common ability for healthy people, however, a certain group of people cannot properly walk due to lower limb diseases. Therefore, gait features have become an important evaluation criterion for ability of walking and assessment of ambulatory behavior. The knee flexion/extension patterns through the gait cycle are also another critical index for gait analysis and biomechanical function in clinics. Hence, if we can monitor gait features and knee angle in a long period of time instantly, it would be helpful for analyzing the disease progression as well as informing rehabilitation practice.

Gait detection and analysis is a common practice to predict the diseases of knee OA [1], Parkinson [2], and stroke [3]. However, many clinical studies can only be conducted in the laboratories or hospitals, and require expensive instruments, like camera-based motion capture system (VICON) [4] or NORAXON [5], which cannot be practically used for monitoring long-term behavior on the subjects. Hence, the predictions for the mentioned diseases are ineffective and untimely such that the succeeding treatments might be even more challenging. On the other hand, for rehabilitation, many hospitals usually use goniometers to evaluate the rehabilitation effectiveness by professional physiotherapists, and patients have to return to hospitals for their daily rehabilitation. This process is time-consuming and inconvenient for elders. Therefore, it is quite desirable for patients to have wearable devices with user-friendly interfaces monitoring their gaits instantly and facilitating the rehabilitation.

This work is supported in part by the Ministry of Science and Technology of Taiwan under MOST 106-2221-E-007-111-MY3, MOST 107-2622-8-007-017-TA, MOST 108-2221-E-155-047, MOST 108-2636-E-007-002, and MOST 108-2218-E-007-061.

Previous studies about measuring lower extremity angle remotely for musculoskeletal pathology have been proposed in [6] [7]. For example, Russell et al. proposed an internet-based approach to evaluate the knee flexion and extension angles using webcams such that a therapist can perform assessments remotely [6]. The main drawback of this approach is that all the positions have to be captured under the webcam and a physiotherapist needs to monitor the motions to obtain the knee angles.

Another approach for measuring knee angles is to use digital photography proposed by Russo et al. [7]. The authors took a digital photograph of the joint, and then analyzed knee angles offline by professional physical therapists. The main limitations of this approach are that it cannot conduct long-term ambulatory measurement of human body; and capturing distance or angle from the camera may significantly affect the accuracy of the photographic measurements.

There are also numerous previous studies about IMU-based gait analysis [8] [9] [10] [11] [12], gait phase detection [13], and assessment of foot orientation [14]. For example, using gyroscopes and flex-sensors to measure the knee angles was proposed by Masdar et al. [8]. They quantified the knee flexion angle by exploiting the relationship between the resistance and the flexion of flex-sensors. However, the flex-sensors may wear out easily such that the knee angle calculated by the changing of resistance will become inaccurate gradually. Furthermore, the flex-sensors may hinder patients from normal walking.

Last, an approach proposed by Feldhege et al. [9] used the scalar product for the tilt estimation of a chest-mounted accelerometer sensor [15] and combines the result with the gyroscope data using a complementary filter [16] for knee angle measurement. However, the complementary filter coefficients were determined empirically and different for various cases. Hence, the accuracy of knee angle calculation may be decreased. Besides, the main axis of knee rotation has to match the z-axes of both sensors, which are attached at the thigh and shank. This limitation also lowers the precision of calculated knee angle due to sensor misalignment. From the viewpoint of user experience, all the data are processed off line and cannot provide the real-time feedback to users.

Fig. 1. The iKneePad system composed of two 9-axis sensors, sport knee pad, and Android APP.

Thus, we propose a system iKneePad that calculates stride counts and walking distance via measuring knee angles by a lightweight wearable device with an Android APP. Our system consists of two 9-axis sensors, which are designed and developed by GYRO SYSTEMS, INC. [17], a knee pad, VELCRO, and an Android APP. In the measurement, we attach the sensors on the thigh and shank segments of knee pad as shown in Fig. 1, and connect them to our APP in Bluetooth. When the knee bends during walking, the real-time knee angle, stride counts, and walking distance will be shown on the APP. To verify the accuracy of measured knee angle, we use IMU-based NORAXON as the ground truth. The accuracy of angle in NORAXON is +/- 1.0° in static and +/- 0.4° when it is moving [18].

II. Method

A. iKneePad design and hardware setup

The smart knee pad system, iKneePad, includes two sensors attached to a knee pad. The sensor contains a microcontroller (TI CC2640), 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer (BOSCH BMI160), 85mAH 3.7V lithium-ion battery, Bluetooth 4.1, and a Micro USB connector for charging. The dimension and weight of the sensor are 38mm x 18mm x 11mm and 5g, respectively. The sampling rate of the sensor is 50Hz, and the error of Euler angles is less than 0.5° in static and less than 2° when sensor is moving. To reduce the angle drift in the integration of angular velocity for having Euler angles, the sensor has a calibration mechanism that refers to magnetic north. The sensor can work well for 22 hours before re-charging. Therefore, we can operate the iKneePad a full day and recharge the sensors when we are sleeping.

The synchronization of the sensors is controlled by the APP under the master (APP) and slave (sensor) mechanism. The APP receives the data from the sensors at every sampling time.

We connect the sensors to the Android APP by Bluetooh 4.1 and the sampling rate of the sensor is 50Hz. The APP can show the knee angle, stride count, and the walking distance in real time.

B. Subjects

We recruited 10 healthy volunteers (5 male, 5 female, 23.3±3.1 years old, 171.4±6.8 cm height, and 52.4±4.3 kg) to participate in the experiments.

C. The angles on thigh and shank segments definition

To calculate knee angles, we use the relative angles on the thigh and shank segments. We define the thigh or shank angle as positive numbers when we counterclockwise rotate our thigh or shank from the gravity direction we stand straight, and as negative numbers when we clockwise rotate thigh or shank segments. For example as shown in Fig. 2(a), when we stand straight, the sensors on the thigh and shank are both aligned to the gravity direction, and the thigh and shank angles are 0°. If we lift the thigh, i.e., the sensor on the thigh counterclockwise rotates 90° from the gravity direction as shown in Fig. 2(b), the thigh angle is 90°. If we clockwise rotate shank angle for 90° from the gravity direction as shown in Fig. 2(c), the shank angle is -90°.

D. Knee angle measurement

The knee angle is defined as EQ(1).

$$Knee\ angle = Thigh\ angle - Shank\ angle \tag{1}$$

A gait cycle begins from the phase of heel-strike as a minimum knee angle, and a maximum knee angle occurs at the mid-swing phase.

We demonstrate the corresponding Euler angles between the sensor and an airplane as shown in Fig. 2(d). For measuring the knee angle, we use two sensors placing on the thigh and shank segments. After wearing the iKneePad, we first calibrate the sensors to obtain the offset angle in the standing position with feet shoulder width apart. Then, we set the initial roll angle as 0° on the both sensors prior to measurement.

After calibration, the roll angles of sensors on the knee pad are both 0° value. The roll angle will be positive by integrating the angular velocity when we counterclockwise rotate the sensors with respect to the X-axis as shown in Fig. 2(e).

At the heel-strike, the thigh angle α is positive, the shank angle β is also positive. The knee angle is (α-β), which is a negative value when $\beta > \alpha$, as shown in Fig. 3(a). On the contrary, the thigh angle α is positive, the shank angle β is negative at mid-swing, as shown in Fig. 3(b). Hence, the knee angle is (α - β) = α + $|\beta|$.

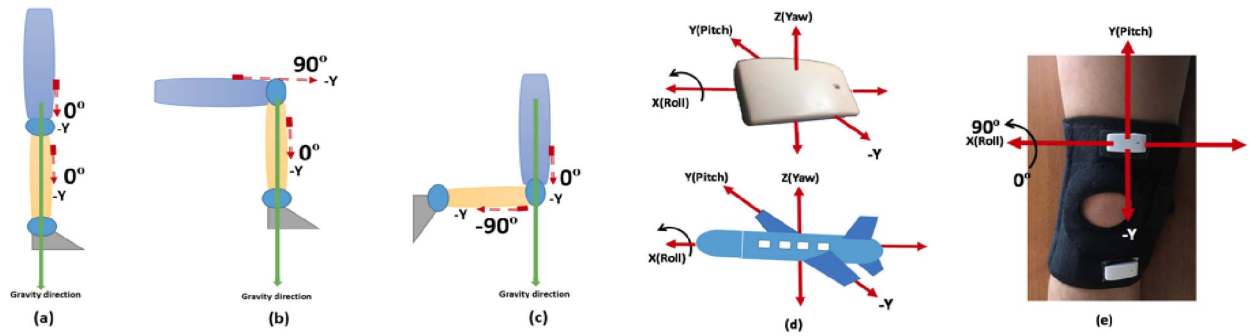

Fig. 2. Blue cylinders represent thigh segments and yellow cylinders represent shank segments. Red small boxes represent the locations of sensors. Green arrows indicate the gravity direction. (a) When standing straight, the sensors on the thigh and shank are both aligned to the gravity direction, and the thigh and shank angles are 0°. (b) If we lift the thigh, i.e., the sensor on the thigh counterclockwise rotates 90° from the gravity direction as shown in Fig. 2(b), the thigh angle is 90°. (c) If we clockwise rotate shank angle for 90° from the gravity direction, the shank angle is -90°. (d) The Euler angles in Gyro sensors and the airplane. (e) The angle is 0° when standing straight.

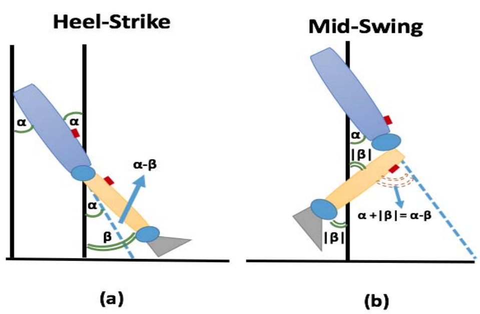

Fig. 3. (a) The knee angle calculation at heel-strike and (b) mid-swing.

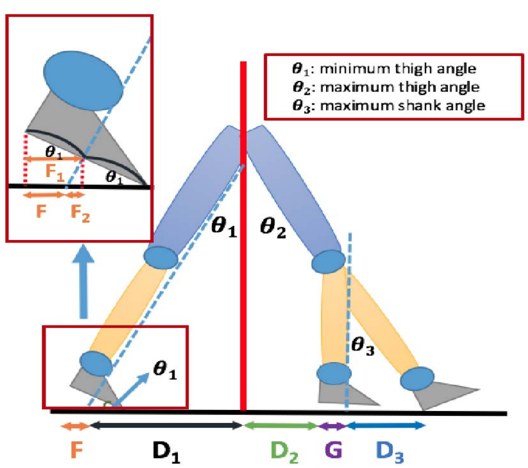

Fig. 4. The stride length measurement by thigh angle, shank angle, thigh length, shank length, and foot length.

E. Stride length calculation

Since we monitor the angles of thigh and shank from one foot instantly during walking, we can use these data to calculate the stride length in a complete gait cycle. A stride length consists of five components D_1, D_2, D_3, F, and G as shown in Fig. 4. The first component is

$$D_1 = (L_T + L_S) \cdot \sin\theta_1$$

where L_T and L_S[1] are the thigh length and shank length, respectively, and θ_1 is the minimum thigh angle. The second component is

$$D_2 = L_T \cdot \sin\theta_2$$

where θ_2 is the maximum thigh angle. The third component is

$$D_3 = L_S \cdot \sin\theta_3$$

where θ_3 is the maximum shank angle. The fourth component is

$$\begin{aligned} F &= F_1 - F_2 \\ &= \tfrac{1}{2} \cdot L_F \cdot \cos\theta_1 - \tfrac{1}{2} \cdot L_F \cdot \tan\theta_1 \cdot \sin\theta_1 \\ &= \tfrac{1}{2} \cdot L_F \cdot (\cos\theta_1 - \tan\theta_1 \cdot \sin\theta_1) \end{aligned}$$

where L_F is the foot length. Here we assume that the thigh is perpendicular to the shoe, and the dash line passes through the middle of foot approximately as shown in Fig. 4. The last component is

$$G = \tfrac{1}{2} \cdot L_F$$

We assume that the knee angle is 0° at heel-rise, and the distance of hip movement can be ignored. Therefore, the summation of D_1, D_2, D_3, F, and G is the stride length.

F. Stride count calculation

We also use the proposed iKneePad system to calculate the stride count based on the regular changes of knee, thigh, and shank angles. Figs. 5(a), 5(b), and 5(c) show the knee angle, thigh angle, and shank angle when an ordinary person walks on the floor, goes upstairs, and downstairs, respectively. Although the angle patterns for these three movements are not the same, their common stride features are extracted and generalized as rules for calculating the stride count.

First, we set 40° of knee angle as the threshold of a stride since knee angle is usually within the range of 40° to 60° during swing for healthy people [19]. If subjects suffer from

[1] Since our experiments were conducted by subjects who put on their shoes walking on a walkway, the heel height is added to the shank length.

walking diseases, e.g., Parkinson or knee OA, we can lower this knee angle threshold to 20°, which is the knee angle during minimum foot clearance (MFC) [20] [21]. Second, we use the changing rates of knee and thigh angles to determine the beginning and the ending of a stride. When a stride starts, the knee angle will increase sharply. The changing rate of knee angle exceeds the threshold of 3°/sample (sampling frequency = 50Hz). By contrast, the knee angle and thigh angle will drop down at the end of a stride. However, since the peak of thigh angle is later than that of the knee angle, the thigh angle is more suitable than the knee angle for recognizing the ending of a stride. As a result, we can obtain all the extremum angles from knee, thigh, and shank before the changing rate of thigh angle is smaller than the threshold of -2°/sample (sampling frequency = 50Hz).

In Fig. 5, the horizontal solid lines label the knee angle at 40° and the vertical dashed lines label the changing rate of thigh angle, which is less than -2°/sample. In summary, we regard 40° knee angle as the beginning of a stride and -2°/sample thigh angle changing rate as the ending of a stride. We conducted six conditions, including (1) knee angle calculation, the stride count calculation of (2) walking, (3) upstairs, and (4) downstairs, and the measurement of (5) short walking distance (10m), (6) long walking distance (33m). The results of minimum and maximum knee angles obtained from NORAXON are as the ground truth for comparing with the results calculated in the iKneePad system.

III. Results

In this section, we show the experimental results demonstrating the accuracy of the proposed algorithm using the iKneePad system.

A. Knee angle calculation

The subjects put on the iKneePad and NORAXON on the right foot as shown in Fig. 6 and stood straight for calibration. Then, the subjects were asked to walk in a straight line for thirty strides. The experimental results are shown in TABLE I. According to TABLE I, the absolute mean errors of maximum knee angle and minimum knee angle are 2.99° and 1.42°, respectively. Since the sensor error is larger under the dynamic circumstance, the absolute mean error of the maximum knee angle is larger than that of the minimum knee angle as expected.

B. Stride count calculation - floor

Since the iKneePad is put on the right foot, a subject was asked to lift their left feet first in the walking condition for successfully collecting data in a complete gait cycle. The subject was also asked to walk in a straight line continuously, and a referee followed him/her for counting the number of strides with a smartphone connecting to the sensors and recording the data. When the subject walked over 100 strides, he/she was asked to stop. The experimental results show that the accuracy of stride count is 100% for all the subjects.

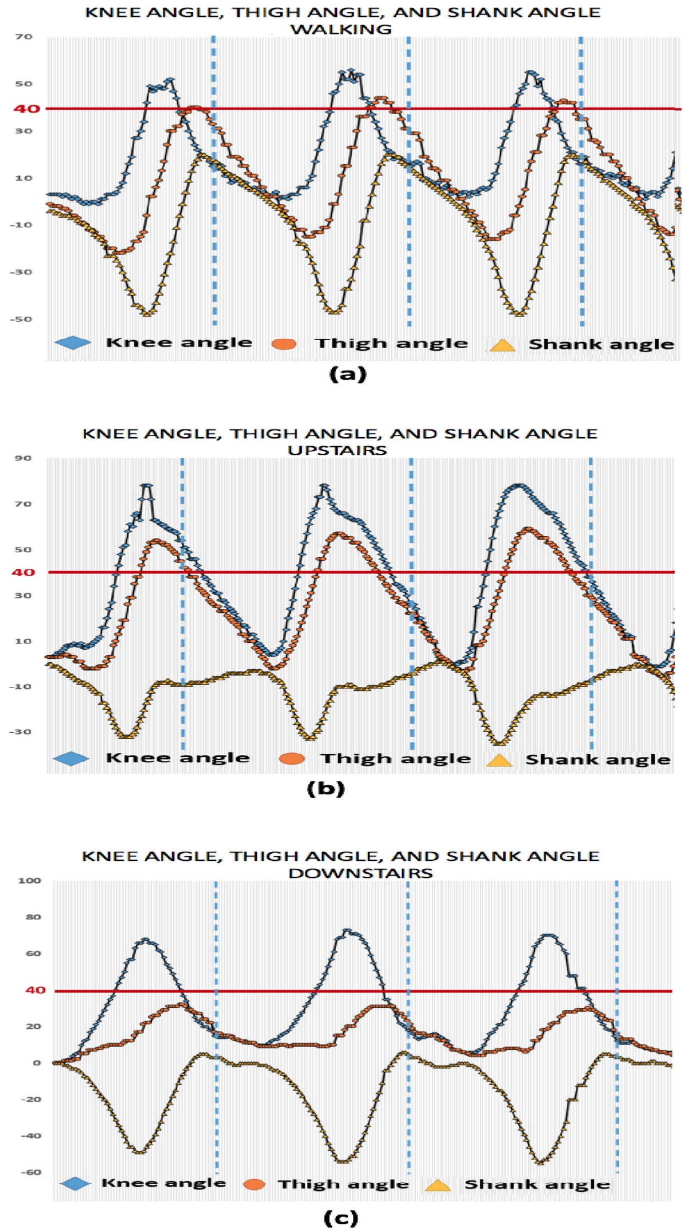

Fig. 5. The knee, thigh, and shank angles during (a) walking, (b) upstairs, and (c) downstairs.

Fig. 6. The experimental setup for knee angle calculation with iKneePad and NORAXON.

C. Stride count calculation - upstairs and downstairs

In this condition, the stride counts about step-by-step and step-over-step were calculated during going upstairs and downstairs. The subject put the iKneePad on his/her right foot. Then he/she was asked to go upstairs and downstairs spontaneously for 5 minutes before calibration. This warm up is for improving the accuracy of experiment by getting used to the elasticity and tightness of the pad. The subject went upstairs and downstairs with his/her left foot leading first for 6 strides in step-over-step condition, and for 12 steps in step- by-step condition. The conditions were conducted for 30 times for each subject. The experimental results show that the accuracy of stride count for going upstairs and downstairs are all 100% for all the subjects.

D. Walking distance measurement

In this condition, we verify the accuracy of the iKneePad for measuring short (10m) and long (33m) walking distances. The subject was asked to perform 30 walking trials at no specific speed over a walkway without knowing the exact travelled distance. When the subject walked over the target distance, we stop the measurement in the APP. The result of each stride is rounded to the nearest tenth in the unit of meter. The walking distance was then summed up by the lengths of all the strides. We used a Gopro camera to record the walking process over a walkway, where every ten centimeters on the walkway was marked. Hence, the ground truth of walking distance can be obtained by examining the video. The error rate of each trial is calculated by EQ(2) where $d^{(m)}$ and $d^{(g)}$ are the measured walking distances, and ground truth, respectively. The mean error rates of short and long distances for all the subjects are shown in the last two columns of TABLE I.

$$error\,rate = \frac{d^{(m)} - d^{(g)}}{d^{(g)}} \times 100\% \quad (2)$$

IV. Discussion

In this paper, we propose a light-weight, wearable, and wireless iKneePad system for calculating the thigh and shank angles. Furthermore, these data are exploited to calculate knee angle, stride count, and stride length instantly during walking, going upstairs, and going downstairs. The accuracy of stride count is 100%, the average errors of knee angle are 2.99° and 1.42° for maximum and minimum flexion angles, respectively. For walking distance, the mean error rate are -2.40% and -2.26% for the short (10m) and long (33m) distance, respectively.

A. Knee angle calculation

The previous wearable solution for calculating knee angles is to exploit the variation of resistance in a sensor device when the knee flexes or stretches [8] [22]. However, the resistance of material in the sensor device may be distorted after flexing for dozens of times. Furthermore, the main limitation of the resistor-based device is that it requires a subject-specific calibration by the motion capture system to obtain the linear function between voltage and flexion angle [22]. The measured knee angle is also inaccurate at the lower range of knee angles due to the characteristic of the device. Hence, this previous work only focused on the peak knee angle measurement with the assistance of a laptop. The mean error it reported was underestimated by summing positive and negative errors. On the contrary, our work can obtain a wide range of knee angle and the reported mean error adopts the absolute value of error to express the accuracy.

B. Stride count calculation

There exist different approaches to calculate the stride count in daily life activity. The approach [23] used the accelerometers in smart phones or smart watches to detect the regular movement of extremities. Another approach [24] [25] used pressure sensors, e.g., Piezo, putting in the shoes, to detect the regular change of the foot pressure for calculating the stride count. However, the accuracies of these approaches were not high enough.

Our approach obtains 100% accuracy on the stride count by observing the regular changes of knee, thigh, and shank angles.

C. Walking distance measurement

The previous studies [25] [26] used the double integral of acceleration to calculate the walking distance by IMU attached to shoes. [25] needs to tune an experimental coefficient K to obtain the distance. The coefficient K is tuned to a value such that the mean value of estimated distance is equal to the reference distance. [26] proposed sensor fusion techniques by using a multisensor model approach that can reduce unbounded growth of error caused by double integral. Our work is a geometric approach to the same walking distance problem. The mean error rates of [25] are 4.8% and 3.1% in short (16m) and long (89m) distances, respectively, while ours are smaller compared with them.

D. Application and limitations

iKneePad system can also be used in clinical experiments for the lower limb diseases. In the applications of sports, e.g., bicycling, soccering, or squatting, the knee angle can be used as an index or an indicator for posture optimization [27] [28]. Furthermore, the patients suffering from cruciate ligament can utilize the system to monitor the knee angle flexion during rehabilitation [29].

The limitation of this method is that the first leading step has to be from the left foot since the pad is equipped in the right foot. If we start from the right foot, we may lose the data of minimum thigh angle and cause the first stride length inaccurate.

V. Conclusion

This paper proposes a light-weight, wearable, and economical iKneePad system composed of two 9-axis sensors, a knee pad, and an Android APP. The iKneePad system can be used for gait assessment by long-term knee angle monitoring. Additionally, the gait features using the thigh, shank, and knee angles can be displayed and recorded on the APP during our daily life. The experimental results show that the accuracy of stride count is 100%,

TABLE I

Table I. The second and third columns show the range of maximum knee angle obtained from the iKneePad system, and NORAXON, respectively. The fourth column shows the absolute mean error of the maximum knee angle. The fifth and sixth columns show the range of minimum knee angle obtained from the iKneePad system, and NORAXON, respectively. The seventh column shows the absolute mean error of the minimum knee angle. The last two columns show the mean error rates of short and long distance, respectively.

Subject	Range of Max Angle iKneePad (°)	Range of Max Angle NORAXON (°)	Absolute Mean Error in Max Angle (°)	Range of Min Angle iKneePad (°)	Range of Min Angle NORAXON (°)	Absolute Mean Error in Min Angle (°)	Mean Error Rate Short Distance (%)	Mean Error Rate Long Distance (%)
1	62∼70	60∼75	3.5	-2∼ 1	-2∼-1	0.9	-1.89	-1.59
2	51∼55	53∼59	2.5	-3∼ 0	-2∼-1	1.3	-1.14	-3.33
3	54∼64	56∼68	2.7	-9∼-2	-7∼-1	1.9	-3.58	-3.48
4	52∼60	47∼56	2.9	-4∼ 2	-4∼-1	1.7	-1.80	-1.76
5	57∼64	56∼70	3.6	-8∼ 2	-5∼ 1	1.4	-1.59	-1.19
6	52∼57	53∼61	2.7	-3∼ 2	-1∼ 2	2.5	-1.51	-1.08
7	44∼50	48∼53	3.4	-2∼ 4	-1∼ 2	1.0	-2.28	-1.94
8	51∼58	53∼60	2.6	-1∼ 3	-1∼ 3	1.2	-3.72	-1.85
9	47∼54	47∼55	3.2	-2∼ 1	-1∼ 3	0.8	-3.48	-3.06
10	48∼56	50∼58	2.8	-4∼ 0	-3∼-1	1.5	-3.01	-3.29
Mean	-	-	2.99	-	-	1.42	-2.40	-2.26

the absolute mean errors of knee angle are 2.99° and 1.42° for the maximum and minimum flexion angles, respectively. For walking distance, the mean error rates are -2.40% and -2.26% for short (10m) and long (33m) distances, respectively.

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