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Evaluation of Markerless Gait Analysis Method Including Out of Camera Plane Rotate Motion During Gait

Yuto ishige[1], Masataka Yamamoto[1,2], Koji Shimatani[3], Yuya Oishi[1] and Hiroshi Takemura[1]

Tokyo University of Science, Department of Mechanical Engineering, Japan[1]
Email: 7521504@ed.tus.ac.jp

Hiroshima University, Department of advanced Science and Engineering,

Prefectural University of Hiroshima, Department of physical therapy, Japan[3]

Abstract: A RGB camera gait analysis system that does not require markers, large space, and preparation can provide valuable information for effective treatment decisions in clinical settings. In this paper, we propose a simple markerless gait analysis method that can measure even if the rotation angle of the foot changes. The proposed method combines OpenPose (OP) and IMU measurement data using a complementary filter as a sensor fusion method to improve the measurement accuracy of the ankle joint angle, which is predicted to be less accurate for gait with a large foot rotation angle. Nine healthy adult males walked at a self-selected comfortable speed in two different foot-progression angle gait conditions. Spatio-temporal parameters and lower limb joint angles in the two gait conditions were measured. The mean absolute error (MAE) and the coefficient of cross-correlation (CCC) were calculated to evaluate the accuracy. The spatio-temporal parameters measured by the proposed method had low MAE compared with a conventional markerless method. The similarity between the changes in the angles of the hip and knee joints and the changes in the angles measured by a three-dimensional motion capture system was found to be very strongly correlated (CCC > 0.7). The MAE of the hip and knee joint angles measured by the proposed method was small compared with a conventional markerless method. In particular, the proposed method was able to improve the measurement accuracy of the ankle angle by using two IMUs. The experimental results suggest that the proposed method can be used for simple and accurate measurement even when the rotation angle of the foot changes. Although the proposed method has some limitations, it has great potential as a simple and reliable gait analysis system in the clinical field.

Keywords: Gait analysis; Markerless System; Sensor Fusion; Complementary Filter

I. INTRODUCTION

Gait analysis is one of the important assessments in the clinical field. In particular, the measurement of the patient's ankle joint angle provides important data for the treatment of ankle-foot orthoses in clinical practice [1]. Three-dimensional motion capture systems (3DMC) are used in gait analysis tools as the gold standard for highly accurate measurement of spatio-temporal and motion parameters. However, 3DMC is difficult to use in clinical settings because it requires a large space, specialized skills, many markers, and is time-consuming. A markerless motion capture system using a depth camera was also proposed as an alternative to 3DMC [2]-[4]. While these methods are easy to measure, there is a considerable error in the ankle joint angle. The reasons for the error in ankle joint angle are considered to be the high joint angular velocity and the short segment compared to other lower limb joints [5], [6]. Depth cameras may not be able to accurately measure fast joint movements due to their low sampling rate. Furthermore, depth cameras are affected by lighting conditions [7].

Manually determining joint angular motion using photographs has been done for a long time. A simple RGB camera without a depth sensor was frequently used in clinical practice for observational gait analysis because of its ease of measurement. Recently, 2D pose estimation systems such as OpenPose (OP) [8] that use RGB cameras have been developed. This system can predict key locations of the human body automatically

Corresponding Author: Hiroshi Takemura. , Tokyo University of Science , Noda Chiba, Japan, Tel: +81-04-7124-1501, Fax: +81-04-7124-1501, E-mail: takemura@rs.tus.ac.jp

from RGB images using convolutional neural networks (CNN). Previous studies have reported that knee joint angle measurements using OPs are more accurate than systems using a single depth camera [7]. Although OPs have the potential to objectively measure joint kinematics and spatio-temporal parameters, little is known about how accurately OPs can measure spatio-temporal parameters and joint kinematics in various gait conditions, such as when the foot has a large angle of travel or rotates.

Motion capture systems using inertial measurement units (IMUs) have also been used for gait analysis. It can measure spatio-temporal and kinematic parameters. However, this method requires a large number of IMUs with built-in high-quality sensors for accurate gait analysis. And drift error is a major problem in motion capture systems using IMU. As mentioned above, each alternative gait system has different problems and limitations in its use in clinical practice. In this study, we propose a simple markerless gait measurement method using one RGB camera and a few IMUs. In the proposed method, hip and knee joint angles and spatio-temporal parameters were calculated from OP key points. Ankle joint angle is calculated from OP and IMU measurement data. Both data are combined using a complementary filter to improve the measurement accuracy. A previous study [2] using a depth camera placed in front of the walking path had problems in estimating the heel contact angle and lower limb joint angle. In this study, the camera was placed on the side of the walking path to improve the measurement accuracy of heel contact angle and lower limb joint angle. The accuracy of the proposed method is evaluated by comparing it with the 3DMC method. In addition, to evaluate the accuracy of the OP only method, the angle of the ankle joint measured by the OP method was compared with that measured by 3DMC.

II. METHODOLOGY

A. Spatio-temporal parameters

Velocity (V), standing time (ST), swing time (SW), and stride were used as these parameters. Data from in force plate in the treadmill was used to calculate these parameters as the gold standard. In the OP, the walking velocity was calculated from the video data using the mean value of the lumbar midpoint velocity in the sagittal plane. The hell contact and toe-off times were defined from the 3DMC and OP data by referring to a previous study [9]. Standing time and swing time were calculated from heel contact and toe off. The gait trials were conducted using a treadmill; the stride was calculated as

$$stride = V_{tr}\, T + (Xheel_{(i+1)} - Xheel_{(i)}) \qquad (1)$$

where V_{tr} indicates the treadmill belt speed and T indicates the stride time based on the defined initial contact time. X_{heel} is the heel key point and marker coordinates of the sagittal plane (X) on the *i* and *i*+1th initial contacts, respectively.

B. Measurement Angle Using OP

The lower limb joint angles from the RGB images were processed as follows. First, the two-dimensional coordinates of 25 key points on the body are calculated from the input RGB camera images using OP (Fig. 1). A 4th order Butterworth low-pass filter (cut frequency: 6 Hz) was used to remove the coordinate noise. Second, the heel contact was determined by referring to the methods of the previous study [9]. The sagittal plane lower limb joint angles were calculated by two vectors corresponding to segments consisting of two key points of the OP model. For example, the knee joint angle was calculated from (2).

$$angle = \cos^{-1} \frac{\boldsymbol{S} \cdot \boldsymbol{T}}{|\boldsymbol{S}||\boldsymbol{T}|} \qquad (2)$$

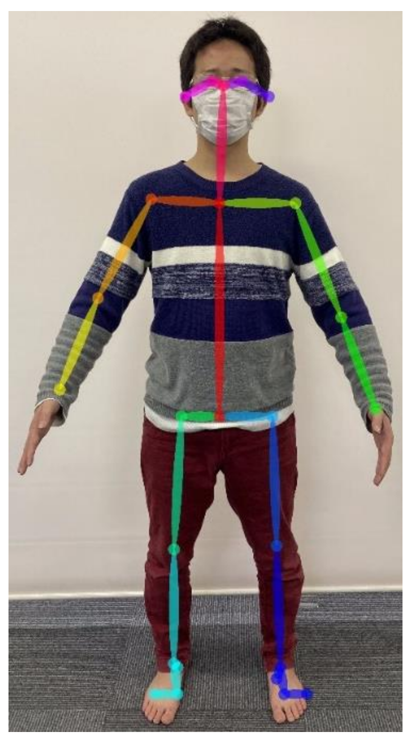


Fig. 1 25 key points from OP.

Here, the thigh vector T (hip-knee) was calculated from the key points at the hip and knee (Fig. 2), and the shank vector S (knee-ankle) was calculated from the key points at the knee and ankle (Fig. 2). The joint angle was calculated from this equation and divided into one walking cycle from heel contact.

C. Correction of ankle joint angle using a complementary filter with OP and IMUs

A complementary filter is a way to improve the measurement accuracy by adding the output of multiple sensors with different effective frequency ranges. It has also been used in previous studies [10] to measure human motion. The angle (θ_i) at time t is calculated by a conventional complementary filter using the following equation:

$$\theta_i[t] = (1 - F)\theta_{IMU}[t] + F\,(\omega_{IMU}[t]\Delta t + \theta_i[t-1]) \quad (3)$$

Where θ_{IMU} is the angle of segment calculated from acceleration, ω_{IMU} is angle velocity from the IMU sensor, Δt is sampling time, F is a filter coefficient. This way is simple to process, has a lower computational cost, and can be as accurate as the Kalman filter for measurement [10].

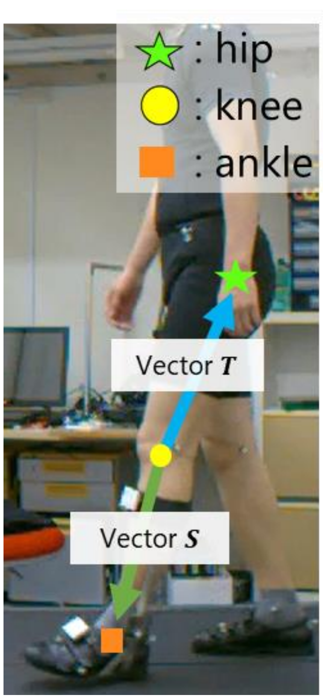
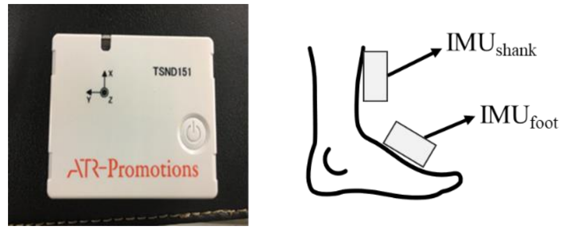


Fig. 2 Vector calculated from key points. These vectors were used when calculating knee joint angle.



(a) IMU (b) Location of IMU

Fig. 3 Photos of the actual IMU(a) and where it was located(b).

To improve accuracy in both gait conditions, IMU (ATR-Promotions, Souraku, Kyoto, Japan) (Fig. 3 (a)) was located in the shank and foot segments (Fig. 3 (b)). These are composed of a triaxial accelerometer with a ±8 [G] range and a gyroscope with ±2000 [dps] ranges. The angle of the ankle is calculated by subtracting $\theta shank$ from $\theta foot$ (Fig. 4). The following process was used to calculate $\theta shank$ and $\theta foot$ by the proposed method. First, the tibia angle and foot angle were obtained from the OP as shown in Fig. 4 . Second, the shank angle and foot angle were obtained from the OP as shown in Fig. 2(b). The obtained acceleration and angular velocity from each IMU were filtered with a 4th order Butterworth low-pass filter (cut frequency 6 Hz) [11] and a 4th order Butterworth high-pass filter (cut frequency 0.5 Hz) [12], respectively. The angular velocity, accelerations, and angular rates obtained from each IMU were filtered by the 4th order Butterworth low-pass filter (cut frequency: 6 Hz) [12].

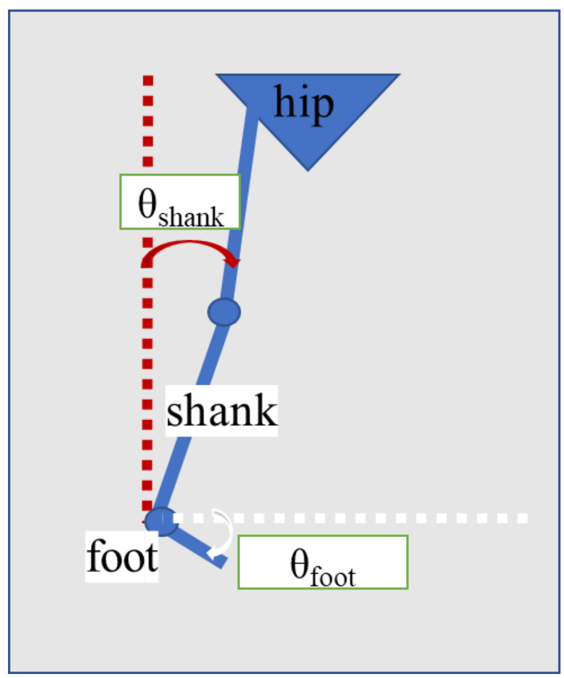


Fig. 4 definition of angles of the shank and foot. The Redline indicates vertical lines. The white line indicates horizontal lines.

$$\theta_{shank}[t] = C\theta_{IMU(shank)}[t] + (1 - B - C)\,\theta_{OP(shank)}[t] + B(\omega_{IMU(shank)}[t]\Delta t + \theta_{shank}[t-1]) \quad (4)$$

$$\theta_{foot}[t] = C\theta_{IMU(foot)}[t] + (1 - B - C)\theta_{OP(foot)}[t] + B\big(\omega_{IMU(foot)}[t]\Delta t + \theta_{foot}[t-1]\big) \quad (5)$$

The joint angle from the OP, the θ_{IMU} is the angle of segment calculated from acceleration and the IMU angular velocity were applied to the proposed three-parameter complementary filter ((4) and (5)). Where, θ_{op} is the angle from the OP, θ_{IMU}, ω_{IMU}, B and C are filter coefficients respectively. Finally, the angle between each IMU was calculated and used as the ankle angle. The values of the filter coefficients in (3) and (4) were determined to have a minimum MAE of the ankle angle under normal conditions (B = 0.96, C = 0.0096).

D. Participant

Nine adult healthy males (mean ± standard deviation (SD), age: 22.9 ± 1.2 years, height: 1.72 ± 0.05 m, weight: 1.8 kg; 58.4 ± 8.4 kg) took part in the study. The below exclusion criteria were used. < 20 years of age, limitation of physical activity due to current injury or illness, history of lower limb surgery, neurological disorders, cardiac disease, and pain while walking. All of our procedures were authorized by the Ethics Committee of the Faculty of Health and Welfare, Hiroshima Prefectural University (15MH036), and we received written informed consent from all participants.

E. Experimental Setup and Procedures

To simulate a clinical situation, an ankle joint orthosis was used and the rotational state of the foot was changed. Participants were told to walk at a self-selected comfort speed on a treadmill (Bertec Corporation, Columbus, OH, USA) in two gait conditions: normal (Normal) and large foot progression angle (FPA) conditions. The FPA on the right side was set by the physiotherapist to a foot progression angle of 50 degrees, which was the large FPA gait condition. After sufficient treadmill gait practice under both gait conditions, the gait trials were measured at 15 seconds. The treadmill belt speed was set to the participant's self-selected comfortable speed on the ground floor condition, which was measured before the experimental measurements. In the proposed method, an RGB camera (Basler, Strusbek Ahrensburg, Germany) was set on the right side at a distance of 3 m from the treadmill to calculate the spatio-temporal parameters of the right lower limb and the joint angle of the right lower limb in the sagittal plane during treadmill walking. For comparison with the proposed method, the spatio-temporal parameters were calculated from the force plate in the treadmill and the joint angles were calculated from 3DMC (NaturalPoint, Corvallis, OR, USA). The sampling rates of the RGB camera, 3DMC, and IMU were all set to 100 Hz, and the force plate was set to a sampling rate of 1000 Hz.

F. Statistical Analysis

Spatio-temporal parameters obtained by the proposed method were compared with those obtained by data from the force plate. To examine the error, the average of Mean Absolute Error (MAE) between the proposed method and force plate was used. Joint angles obtained by the proposed method were compared with those obtained by the 3DMC method. To examine the error in one gait cycle, the average of MAE overall gait cycle of angle from 3DMC and angle from the proposed method or anglefrom the OP only method was used. In addition, the maximum cross-correlation coefficient (CCC) between the angle by 3DMC, and the angle by the proposed method or the angle by OP only was used to examine the similarity of the angle changes in one walking cycle. CCC > 0.7 (or < -0.7) means that the coupling is strong. Coefficients of 0.3 to 0.69 and -0.3 to -0.69 indicate moderate bonding, while coefficients of -0.3 to 0.3 suggest weak or no bonding [13]. Statistical analysis in comparison of CCC and MAE has used the paired student's t-test. Wilcoxon's test was used to compare data without normality. Statistical significance was set at p<0.01.

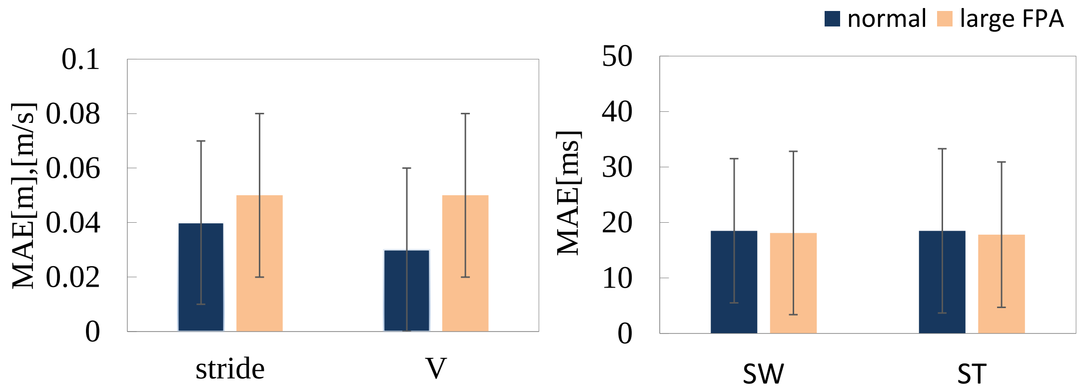
III. RESULT

A. Spatio-temporal parameters.

In fig. 5, the MAE of the spatio-temporal parameters under each walking condition measured by the proposed method is shown. There was a significant difference (p < 0.01) in spatial parameters between the two gait conditions.

B. Kinematics Parameters

In Fig. 6, the mean hip and knee joint angles during walking are shown. The angles of the hip and knee joints were almost the same in the visual comparison between the OP only and the 3DMC. The MAEs for each walking condition measured by the OP-only method are compared in Fig. 7. Significant differences (p<0.01) were found in the angles of the knee and ankle joints between the two walking conditions.



(a) spatio parameter (b)temporal parameter

Fig. 5 MAE of Spatio-temporal parameters

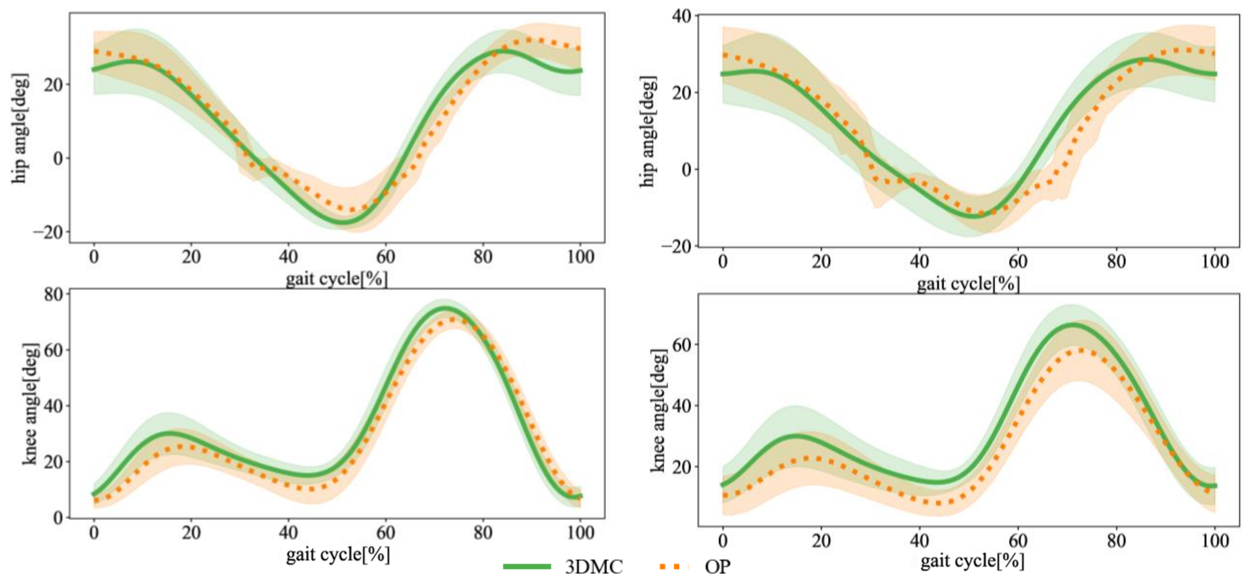


Figure 6. Hip and knee joint angle measured by 3DMC (green) and OP only (orange dot). Angle in normal condition is left and in large FPA condition is right. The shade indicates ±1SD.

The CCC (mean ± SD) of hip, knee, and ankle angle in normal gait condition were 0.97 ± 0.01, 0.98 ± 0.01, and 0.93 ± 0.04, respectively. Additionally, The CCC in large FPA gait conditions were 0.94 ± 0.02, 0.98 ± 0.01, and 0.77 ± 0.14, respectively.

Fig. 8 shows the comparison of the MAE in ankle joint angle measured by the OP only method and the proposed method. The average of ankle joint angles during gait measured by the proposed method (OP&IMU) were shown in Fig. 9. In ankle angle measurement, the MAE in the proposed method significantly decreased compared to the OP only method in both conditions ($p < 0.001$). Moreover, CCC of ankle joint angle measured by the proposed method was 0.94 ± 0.03 in normal gait condition and 0.83 ± 0.13 in large FPA gait condition. In both gait conditions, CCC is between 0.75 to 0.95 by the proposed methods. The CCC of ankle angle in normal and large FPA gait conditions were significantly increased the proposed method than the OP only method ($p = 0.009$ and $p = 0.006$, respectively).

IV. DISCUSSION

In this study, a simple markerless gait analysis method using one RGB camera and a small number of IMUs is

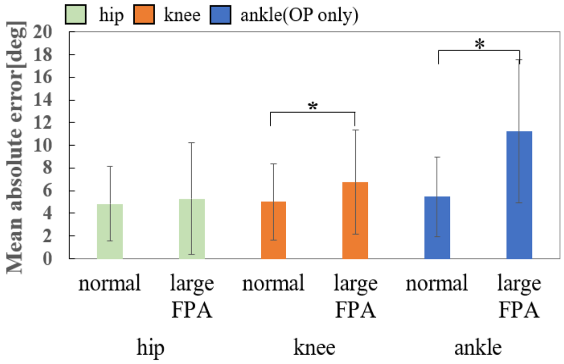


Fig. 7 MAE of each angle in both conditions. MAE measured by the OP only method or the OP&IMU. *indicates $p < 0.01$. error bar indicates ±1SD.

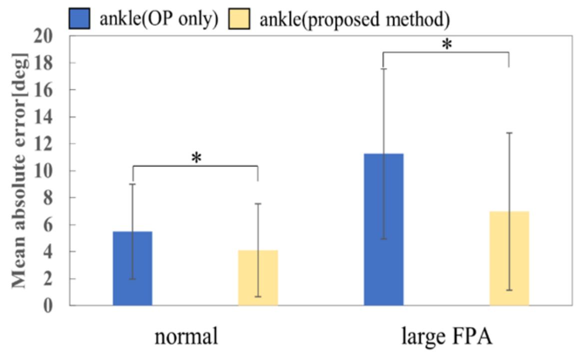


Fig. 8 MAE of each angle in both conditions. MAE measured by the OP only method. *indicates $p < 0.01$. error bar indicates ± 1SD.

proposed. In terms of spatio-temporal parameters, there was a significant difference between the conditions in terms of spatial indicators. This is because the calculation of length is based on the number of pixels in the foot segment and the size of the shoe. In the Large FPA condition, the error was larger because of the external rotation of the foot. However, the error was small in both conditions. Therefore, the proposed method could be used to measure spatio-temporal parameters.

In terms of kinematic parameters, the MAE of the hip and knee joint angles was less than 8 degrees, despite measurements by the OP only. In the measurement of joint angles using a single depth camera [2], the root means a square error of the hip and knee joint angles was more than 10 degrees. Therefore, the OP could be used to measure the motion of the hip and knee joints. However, the CCC of the ankle angle for OP only and 3DMC was more than 0.7 in both conditions, while the MAE in the large FPA condition was more than 10 degrees. This result suggests that the OP may not be measuring the angle of the ankle joint accurately. As reported in previous studies [5], [6], there may be a large error in the measurement of the ankle joint angle because the angular velocity of the ankle is large and changes rapidly in a short time, the range of motion of the ankle is smaller than that of other joints, and the length of the foot segment is shorter than that of other segments. In addition, since the large FPA state, which is essentially a three-dimensional motion as well as a spatio-temporal parameter, was analyzed using a two-dimensional image taken from the right lower limb side, the information on the direction of rotation was insufficient, resulting in a decreased accuracy. On the other hand, the MAE of the

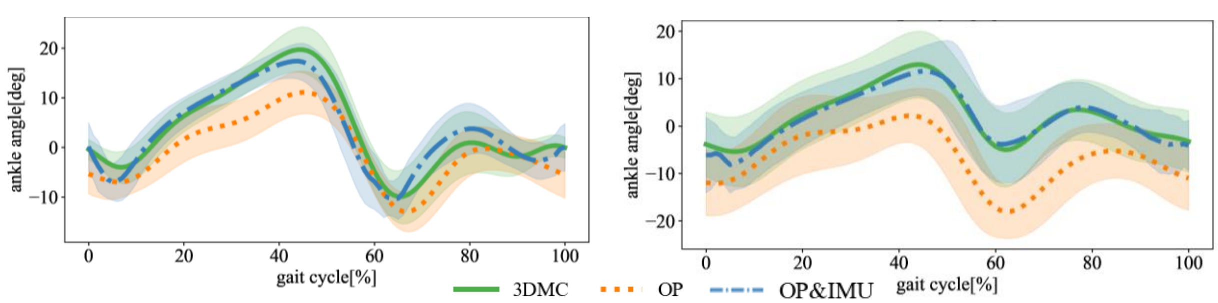


Figure 6 Ankle joint angle measured by 3DMC (green line), OP only (orange dot), and OP&IMU (blue dot dash). Angle in normal condition is left and in large FPA condition is right. The shade indicates ± 1SD.

ankle joint angle by the proposed method was less than 7 degrees in both conditions. This error is smaller than previous studies using a single depth camera [3], [4]. The correction by IMU reduced MAE and improved CCC values in both gait conditions, and there was a significant difference (p<0.01) between the OP-only method and the proposed method. This may be because the IMU reduced the error caused by the lack of information on angular velocity and direction of rotation. In conclusion, it is suggested that the proposed method is effective in improving the accuracy of ankle angle during walking. There are several limitations to this study. First, the number of participants was not very large. Second, the participants only walked on a treadmill. Therefore, future studies need to investigate walking on the ground for a larger number of participants. Despite these limitations, this markerless and simple gait analysis method seems to have the potential to measure gait locomotion in clinical settings.

V. CONCLUSION

In this paper, the simple marker-less gait analysis method for gait with large angle rotates. This method uses a single RGB camera and few IMUs. In terms of spatio-temporal parameters, the error is small. In terms of kinematics parameters, the CCC in the proposed method was higher than the CCC in the OP only method. Moreover, the MAE of lower limb joint angles in the proposed method was smaller than the OP only method or the previous markerless gait assessment system. The experimental results suggest that the proposed method can be used for gait assessment easily and with high accuracy in clinical sites.

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