Comparison of Camera based and Inertial Measurement Unit based Motion Analysis

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Abstract: Camera-based 3D motion analyzers are widely used to analyze body movements and gait, but they are expensive and require a large dedicated space. This study investigated whether inertial measurement unit (IMU)-based systems can replace such systems by analyzing kinematic measurement parameters. IMUs were attached to the abdomen and thigh and the shank and foot of both legs. The participant completed a 10 m-gait course 10 times and the hips, knees, and ankle joints were observed from the sagittal, frontal, and transverse planes during each gait cycle. The experiments were conducted with both a camera-based system and an IMU-based system. The measured gait analysis data were evaluated for validity and reliability using RMSE. In this regard, the differences between the RMSE values of the two systems determined through kinematic parameters ranged from a minimum of 1.39 to a maximum of 3.86. These results confirm that IMU-based systems can reliably replace camera-based systems for clinical body motion analysis and gait analysis.

1 INTRODUCTION

The level of improvement in gait and quantification of body motion corroborate clinical decisions in the treatment process and is used for functional assessment in clinical gait analysis and rehabilitation. Interest in gait evaluation and gait improvement is increasing for non-patients as well as young persons who have abnormal gait. Gait analysis has evolved from a simple 2D video camera analysis to optical motion capturing using several infrared cameras and 3D motion analysis systems. The 3D motion analyzers currently widely used for gait analysis record body motion by reading location coordinate values of body markers attached to in body in real time with several infrared cameras in a limited space.

However, both the purchase price and maintenance of these motion analyzers are high. Further, in order to take measurements from various angles, several cameras and much space are required. In addition, because such systems have to be installed by professionals and require complex setup and preparation for experiments and data analysis, they are difficult to apply in clinical settings.

Under different experimental conditions and environments, the measurements obtained can also differ based on the setting's characteristics. Consequently, issues concerning the validity and reliability of the measurements obtained from these machines also exist. With the aim of developing systems that are without the disadvantages outlined above, in recent times, research has been focused on gait analysis using inertial measurement units (IMU).

Recent advancements in sensor technology enable simple and economic analyses to be performed using IMUs. The inertial sensors usually comprise a gyroscope, an accelerometer, and a magnetometer, which enable economical measurements of gravitational force and acceleration. Changes in the Euler angle, yaw, pitch, and angles of rolling axis can also be measured using the gyroscope.

Numerous studies on gait analysis using inertial sensors have focused on detection of gait phase, and measurement of joint angles, segment angles, and stride lengths. The results of these studies indicate

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that wireless inertial sensor systems on the lower body could analyze and evaluate the characteristics of gait.

However, gain analysis data from the use of inertial sensor systems are scarce. Furthermore, because the technology is not considered fully complete, inertial sensor systems are not widely used for clinical gait analysis. Furthermore, their accuracy is in doubt. In this study, the accuracy of IMU-based sensor systems was investigated through spatial-temporal and kinematic parameters on the same subject and comparison with results from camera-based 3D motion capture systems to determine whether IMU-based systems can replace camera-based systems.

In this study, a gait analysis system that analyzes and quantifies the kinematic data of a specific part of body was developed. Further, measurements obtained from wearable IMU sensors on the lower limb were compared to those from a camera-based optical motion capture (OMC) system and their validity evaluated. In addition, tests were conducted in multiple settings to confirm the reliability and effectiveness of IMUs. To the best of our knowledge, no studies have reported on the reliability of IMUs. Thus, confirmation of IMU effectiveness and its accuracy will provide important reference data for further studies in related fields. The developed system can be applied in clinical and rehabilitation settings.

2 MATERIALS AND METHOD

2.1 Participant and Gait Measurement

The subject of this study was a healthy adult male with no musculoskeletal disabilities (age: 40s, height: 180 cm, weight: 90 kg). The experiment was conducted in three different hospitals (National Rehabilitation Center, Veterans Health Service Medical Center and Yonsei University Hospital) between March 2016 and May 2016.

Each hospital had all the necessary equipment to simultaneously conduct gait pattern analysis for both the camera-based and IMU-based systems (Fig. 1).

In addition, the procedures in this test were performed with the approval of Hanyang University Guri Hospital (IRB File No. GURI 2015-03-001-003).

The participant completed a 10 m-gait course 10 times in each experimental setting. During the gait cycle, the kinematic parameters of hip, knee, and ankle joint were inspected from the sagittal, frontal, and transverse planes. In addition, the temporal-spatial parameter was inspected. All experimental trials were conducted in identical conditions.

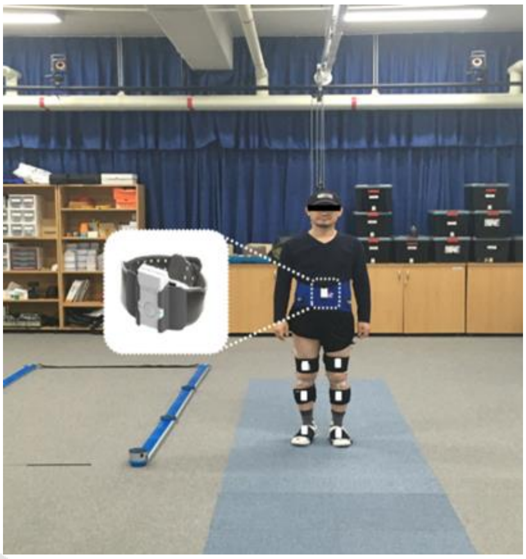

Figure 1: Camera-based system and IMU-based system.

2.2 Experiment Equipment and Procedure

For gait pattern analysis, the camera-based system comprised VICON MX-T10 (Vicon Motion Systems Ltd., Oxford, UK), which is the most widely used system, and Motion Analysis (Raptor-E Digital Real Time System; Motion Analysis, Santa Rosa, CA, USA). The IMU (35 mm × 60 mm × 25 mm)-based gait analysis system (Motion Track, R. Biotech Co., Ltd., Seoul, Korea) consisted of gyroscope, accelerometer, and magnetometer sensors.

To evaluate the validity of the IMU, a reflective marker-based 3D infrared camera system was simultaneously used. The markers, used to analyze the lower limb motion during gait were attached to body using the plug-in-gait marker set method. Wearable wireless IMUs were attached to the abdomen, femur, tibia, and foot of both legs and affixed with stretch bands. As shown in Fig. 2, the IMU sensors were placed on a holder to increase stability and accuracy (Fig. 2).

Each sensor's signal was received and collected using Bluetooth communication. The spatio-temporal (gait cycle time, stance, swing phase, velocity, distance, etc.) and kinematic (hip, knee, ankle angle in three dimensions) data were calculated using MATLAB® (ver. 2010a, MathWorks Inc., USA). Before the actual measurements, the participant underwent several trials with the markers and IMUs attached in order to familiarize himself with the gait conditions.

The validity of the gait analysis was analyzed using the root mean square error (RMSE) of parameters simultaneously obtained through the camera-based system and the IMU-based system. The reliability of the IMU was inspected using the RMSE of kinematic parameters measured with the IMU in three different experimental settings with a certain time interval between each.

Figure 2: Hardware design of the IMU (the sensor was placed in the holder).

2.3 Attitude and Heading Reference Systems (AHRS) Module

In this study, inertial sensor-based AHRS was designed and developed. When attached to the body joints, the AHRS could measure the kinematic motions of each joint objectively. In addition, the AHRS measured the direction of the gravity and magnetic field of the earth.

The AHRS module is composed of inertial sensor, a microcontroller for receiving and processing the signals, a Bluetooth module for communication, and a battery charging circuit.

The inertial sensor used for the module in this study was an integrated sensor (MPU9250, Invensense, USA) composed of a gyroscope (range ± 2000 °/s), an accelerometer (range ± 16 g), and a magnetometer (range ± 49 G). The signals were programmed to be transmitted to the microcontroller through SPI communication at 100 Hz in each signal. The collected angular velocity, acceleration, and magnetometer values were combined and the gradient descent algorithm used to calculate the Euler angle, yaw, pitch, and roll of the AHRS module. The calculated values were transmitted to a PC using a wireless Bluetooth module (PAN1321i, Panasonic, Japan).

On the basis of the data from the magnetometer, which provides data on the earth's magnetic field using the gradient descent algorithm, and data from the accelerometer, which provides data on the gravity and inertia, the gyroscope's inaccurate measurement of angular velocity was supplemented and integrals were conducted to calculate and reliably determine the Euler angle.

2.4 Gait Event Detection and Temporal Parameters Calculation

The differential calculated from the foot's Euler angle determined the gait event, as shown in Fig. 3, and the temporal parameters of gait were also suggested. Fig. 3 explains the algorithm used to determine the temporal parameter using gyroscope on the foot. The figure shows the quantification of the gyroscope features during the gait cycle of each foot observed from the sagittal plane.

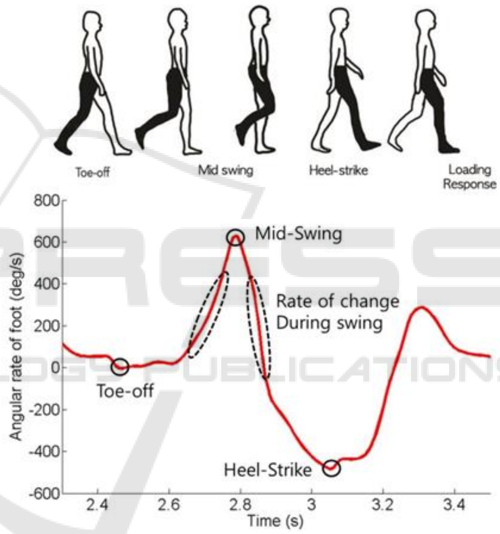

Figure 3: Graphical illustration of the algorithm used to determine the gait event using rotation angle on the foot.

The inertial sensor data based on the verified algorithm detected the heel strike (HS) and toe-off (TO) points.

Peak rotation rate is the maximum achieved rotation rate of the ankle during the swing phase. The minimum value of TO is the minimum value larger than the peak rotation value at mid-swing. In addition, at HS, the peak of the negative rotation value is observed at the first minimum after the maximum rotation rate during the mid-swing period.

After the detection of HS and TO, the gait cycle was formed to calculate gait temporal parameters. Based on these time events, the temporal parameters swing phase and stance phase can be calculated using Eqs. (1) and (2), respectively.

Swing Phase, SW:

$$\mathrm{SW}(k) = \mathrm{HS}(k+1) - \mathrm{TO}(k) \tag{1}$$

Stance Phase, ST:

$$\mathrm{ST}(k) = \mathrm{GCT}(k) - \mathrm{SW}(k) \tag{2}$$

2.5 Spatial Parameters Calculation

In spatial parameters calculation, the distance traveled by the subject is determined by the double integration of momentary accelerations measurements. The position or distance values obtained by the integration is known to be suitable only for a short term because of the drift error of the accelerometer. In other words, calculation of velocity and distance using the double integration of acceleration measurements produced a relatively large accumulated error. To avoid this accumulated error, the values should be measured after every step the pedestrian takes. If the velocity and distance estimations are measured in each step, the successive measurements of speed and distance are not affected. Therefore, the accumulated error of the AHRS was corrected. Fig. 4 shows a schematic diagram of the two-phase cumulative error reduction algorithm used to minimize the accumulated error of the double integration, which was calculated using the acceleration values and angular velocity from the AHRS modules.

Velocity and distance were calculated by double integrating the acceleration measurements. The gravitation influences and accumulated error were removed in order to calculate accurate values.

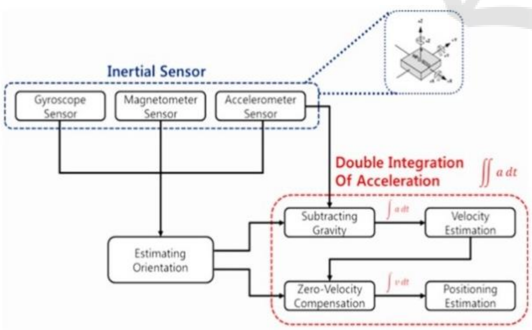

Figure 4: Spatial parameters calculation algorithm.

2.6 Calculation of Joint Angles

In order to measure the joint angles during rehabilitation gait analysis, a total of seven AHRS system modules were attached to the participant's joints. The modules were attached to the abdomen, bilateral femurs, bilateral tibias, and the feet using a stretch band, and the angle joints were calculated using the Euler angles obtained from each joint. An algorithm to calculate joint angles, which are important biological measurement for rehabilitation, was also developed in this study.

Fig. 5 shows a conceptual map of the algorithm that calculates the joint angle in each segment. The conceptual map uses the joint angle between the femur and the tibia as an example. The example shows the method used to calculate the angle between the femur and tibia; the same algorithm can be applied to other segmental joint angles.

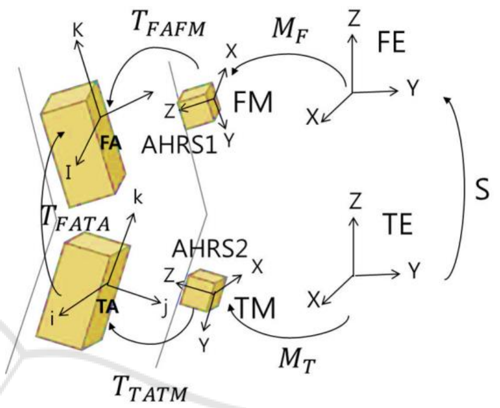

Figure 5: Conceptual map of segmental joint angle calculation method.

Fig. 5 represents tibia anatomical (TA) and femur anatomical (FE), and each sensor axis was labeled as tibia measurement (TM) and femur measurement (FM). To convert the axis of each sensor into one single axis, conversion matrix $T_{TATM,}$ which is a matrix in which the sensor axis is converted to tibial axis, and $T_{TAFM,}$ which is a matrix in which the sensor axis is converted to femoral axis, were used. The ultimate matrix that representing the joint angle between the two sensors is expressed in Eq. (3).

$$T_{FATA} = T_{FAFM} M_F S M_T^{-1} T_{TATM}^{-1}$$

$$T_{FATM} = T_{TATM} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \tag{3}$$

In Eq. (3), S represents the alignment matrix between two axis sensors of the earth (FE and TE) while M_F *and* M_T represent the direction of the femur and tibia relative to the earth axis. As shown in Eq. (4), T_{FATA} matrix terms were used to calculate the joint angles flexion/extension, abduction/adduction, and internal/external rotations:

$$\mathrm{Flexion/Extension} = tan_2^{-1}\left(\frac{-T_{FATA}(2,3)}{T_{FATA}(3,3)}\right)$$

$$\mathrm{Abduction/Adduction} = sin^{-1}(T_{FATA}(1.3)) \tag{4}$$

$$\text{Internal/External} = tan_2^{-1}\left(\frac{-T_{FATA}(1,2)}{T_{FATA}(1,1)}\right)$$

3 RESULTS

In order to evaluate the performance of the gait analysis system, the segmental joint angles on both lower limbs were measured with seven AHRS system modules. The attachment locations were the abdomen, bilateral femurs and tibias, and the feet. Based on the Euler angles of each joint provided by the individual modules, the joint angles were calculated with the joint angle calculation algorithm. The Euler angles obtained from the AHRS in segmental joints while the participant completed the 10 m-gait course were used to calculate joint angles and 10 trials were conducted for measurement under identical protocol.

Table 1 shows the inspection results for the validity of the IMU-based system. The validity was evaluated by comparing the temporal and spatial parameters of the gait measured by the camera-based and IMU-based systems in the three separate hospitals.

The velocity measured with the IMUs was in the range 1.16−1.20 m/s, whereas that measured with the camera-based system was in the range 1.23−1.31 m/s. The stride lengths measured with the IMUs and the camera-based system were in the ranges 1.15−1.27 m and 1.19−1.32 m, respectively.

The stance phase (%) measured with the IMUs was in the range 56−58%, whereas they were in the range 61−63% for the camera-based system. The swing phases (%) measured with the IMUs and the camera-based system were in the ranges 42−44% and 37−39%, respectively. Overall, the values measured with the two systems did not show significant differences.

Table 2 shows the inspection results for the validity related to kinematic parameters of the IMU-based system obtained by comparing the gait data measured with camera-based and IMU-based systems in three different hospitals. In order to analyze the accuracy of the IMUs, the differences in lower limb joint angles measured with the two systems are shown. On the basis of the Euler angles obtained from the AHRS modules on each body segment, the segmental joint angles during gait cycle were calculated. The values were processed in a 3D space on the sagittal, frontal, and transverse planes.

Table 1: Temporal and spatial parameters of the camera-based system and the IMU-based system obtained in the three separate hospitals.

		Velocity (m/s)	Stride length (m)	Stance phase (%)	Swing phase (%)
National Rehabilitation Center	IMU	1.20	1.23	58	42
	Vicon	1.31	1.19	63	37
Veterans Medical Center	IMU	1.18	1.27	58	42
	Motion analysis	1.25	1.32	61	39
Yonsei University Hospital	IMU	1.16	1.15	56	44
	Vicon	1.23	1.23	61	39

The RMSE values of each of the sagittal, frontal, and transverse planes are shown in Table 2. The average RMSE value of the ankle joint angle on the frontal plane was the lowest at 1.60. In addition, the RMSE value of the ankle joint angle on the transverse plane was the highest at 3.82. The results verify the validity of the IMUs. The RMSE values obtained at the hospitals are shown in Table 2.

Table 2: Kinematic parameters for the camera-based system and the IMU-based system obtained at the three hospitals.

		National Rehabilitation Center	Veterans Medical Center	Yonsei University Hospital	Average RMSE
Sagittal	H	1.80	1.46	2.14	1.80
	K	2.87	2.37	2.91	2.72
	A	1.63	2.26	1.43	1.77
Frontal	H	3.48	1.57	2.68	2.58
	K	1.77	2.13	2.08	1.99
	A	1.39	1.81	1.60	1.60
Transverse	H	3.86	3.72	4.25	3.94
	K	2.99	3.01	2.95	2.95
	A	2.88	3.35	5.23	3.82

H: RMSE of Hip Joint angle, K: RMSE of Knee Joint angle A: RMSE of Ankle Joint angle

4 DISCUSSION

It has been reported that the mechanical accuracy of IMUs could produce errors when measuring body movements such as joint angle measurements. During the measurement of acceleration and angular velocity, the measurement plane of the IMU modules on the body did not mechanically coincide because of the curves on the body.

In this study, a camera-based system was simultaneously used with the IMU-based system. The differences between the RMSE values of the two systems determined through kinematic parameters with a tolerance close to 1%. Therefore, the comparison results of two systems indicate that IMU-based systems can replace camera-based systems. The errors in joint angles during gait analysis are within the tolerance range and the errors could be reduced by replacing the gyroscope, accelerometer, and magnetometer sensors with an integrated sensor.

Further, the RMSE values of the kinematic parameters measured with the IMU-based systems in the three different experimental settings with a tolerance close to 1%. Therefore, it can be inferred that IMU-based systems are reliable for gait analysis. Compared to the 2% error rate reported by previous studies that used relatively more expensive sensors, this study showed similar performance with those studies that used high-cost sensors.

The limitations of this study include the fact that the study was conducted on one participant and the measurement session was extended over a long period. Although the healthy participant tried to maintain his health and physical activities for three months during the experimental trials, the measurements in different hospitals were taken over an extended period.

Further studies on IMU-based gait analysis will attract increased attention and demand. Therefore, a system that provides feedback for gait correction and evaluation will be developed in future work..

5 CONCLUSIONS

Gait analysis is currently conducted very rarely owing to high equipment cost, complex procedure, and space restriction. Therefore, an IMU-based system was inspected to verify its validity and its potential to replace camera-based systems. The results indicate that IMU-based systems can be effectively used in clinical settings and could be applied to other fields that require gait analysis. Furthermore, it is expected to be widely distributed in related fields. Because IMU-based systems provide accurate gait data in real time, they could contribute to faster diagnosis and evaluation by physicians.

This study verified the validity and the reliability of IMU-based systems. The results indicate that IMU-based systems can be widely used for rehabilitation and gait analysis in clinical settings. It will be necessary to develop interaction-coaching systems to improve the accessibility of such systems. In addition, a new type of gait analysis system that portrays gait data as graphs, 3D avatars, and webcams should be developed. The development of IMU-based systems is expected to improve the quality of patients' lives as the cost for gait analysis will consequently decrease.

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