Original Article

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Evaluation of Validity and Reliability of Inertial Measurement Unit-Based Gait Analysis Systems

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Objective To replace camera-based three-dimensional motion analyzers which are widely used to analyze body movements and gait but are also costly and require a large dedicated space, this study evaluates the validity and reliability of inertial measurement unit (IMU)-based systems by analyzing their spatio-temporal and kinematic measurement parameters.

Methods The investigation was conducted in three separate hospitals with three healthy participants. IMUs were attached to the abdomen as well as the thigh, shank, and foot of both legs of each participant. Each participant then completed a 10-m gait course 10 times. During each gait cycle, the hips, knees, and ankle joints were observed from the sagittal, frontal, and transverse planes. 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 root mean square error (RMSE) and intraclass correlation coefficient (ICC) analyses.

Results The differences between the RMSE values of the two systems determined through kinematic parameters ranged from a minimum of 1.83 to a maximum of 3.98 with a tolerance close to 1%. The results of this study also confirmed the reliability of the IMU-based system, and all of the variables showed a statistically high ICC.

Conclusion These results confirmed that IMU-based systems can reliably replace camera-based systems for clinical body motion and gait analyses.

Keywords Gait analysis, Kinematics, Inertial measurement unit, Motion capture system, Rehabilitation

INTRODUCTION

The level of improvement in gait and the quantification of body motion are two measures that corroborate clinical decisions in the treatment process, and are used for functional assessment in clinical gait analysis and

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rehabilitation [1-3]. There has been increasing interest in gait evaluation and improvement non-patients and young persons who have abnormal gait. Gait analysis has evolved from simple, two-dimensional video camera analysis to optical motion capture using several infrared cameras and three-dimensional (3D) motion analysis systems [4,5]. The 3D motion analyzers currently widely used for gait analysis record body motion by reading the location coordinate values of body markers attached to the body in real time using several infrared cameras in a limited space.

However, both the purchase prices and maintenance costs of these motion analyzers are high. Furthermore, several cameras and substantial amounts of space are required to take measurements from various angles. In addition, these systems are difficult to apply in clinical settings, because they have to be installed by professionals and require complex setup and preparation for experiments and data analysis [6-9].

Under different experimental conditions and environments, the measurements obtained can also differ based on the setting's characteristics. Consequently, there are issues concerning the validity and reliability of the measurements obtained from these machines [10]. With the aim of developing systems that address the disadvantages outlined above, recent research has focused on gait analysis using inertial measurement units (IMUs) [11,12].

Recent advancements in sensor technology have enabled simple and economic analyses to be performed using IMUs. The inertial sensors used usually comprise a gyroscope, an accelerometer, and a magnetometer, which enable economical measurements of gravitational force and acceleration [6,13-17]. Changes in the Euler angle, yaw, pitch, and angle of the rolling axis can also be measured using the gyroscope [18].

Numerous studies on gait analysis using inertial sensors have focused on detecting the gait phase and measuring the joint and segment angles and stride lengths [19-21]. The results of these studies have indicated that wireless inertial sensor systems on the lower body can help analyze and evaluate gait characteristics [7].

However, the gait analysis data from these inertial sensor systems lack validation and reliability. Furthermore, inertial sensor systems are not widely used for clinical gait analysis because the associated technologies are not well developed; their accuracy is also doubtful [9]. This study investigates the accuracy of IMU-based sensor systems through the spatio-temporal and kinematic parameters of the same subject, and compares the findings with the results from camera-based 3D motion capture systems in order to determine whether IMU-based systems can replace camera-based systems.

Accordingly, a gait analysis system that analyzes and quantifies the kinematic data of a specific part of the body is developed.

Previous studies on IMU-based systems have largely been validated in the sagittal plane [20-22]. However, our study verified not only the joint angle, but also the temporal and spatial parameters in the sagittal, frontal, and transverse planes as well.

The 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 was evaluated. Tests were conducted in multiple settings so as to confirm the reliability and effectiveness of IMUs. Our study presents the evaluation of an IMU-based gait analysis system in several laboratories with camera-based systems in order to verify its reliability among several operators.

MATERIALS AND METHODS

Participant and gait measurement

The study subjects were healthy adult males with no musculoskeletal disabilities (three males: age, 38.3±2.9 years; weight, 78.0±10.4 kg; and height, 179.0±2.6 cm). The experiment was conducted in three different hospitals (i.e., National Rehabilitation Center, Veterans Health Service Medical Center, and Yonsei University Hospital) between March 2016 and May 2016.

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

The participants were thoroughly informed about the purpose, experimental methods, procedures, and precautions of the study prior to the experiment. They also provided written informed consent. The procedures in this test were performed with the approval of the Hanyang University Guri Hospital (IRB No. GURI 2015-03-001-003).

Each participant completed a 10-m gait course 10 times in each experimental setting. The kinematic parameters

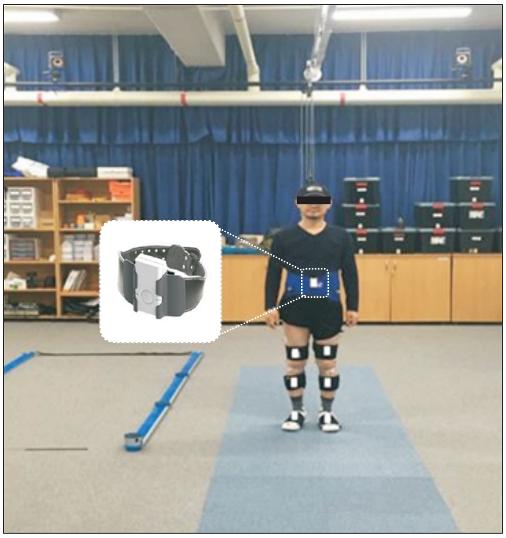

Fig. 1. A subject has inertial measurement units on both dorsa of the feet, shafts of the tibias, middles of the femurs, and the lower abdomen in the room where the camera-based system is installed.

Fig. 2. The inertial measurement unit sensor is placed on a holder so as to increase stability and accuracy.

of the hip, knee, and ankle joint during the gait cycle were inspected from the sagittal, frontal, and transverse planes. In addition, the spatio-temporal parameter was inspected. All experimental trials were conducted in identical conditions.

Experimental equipment and procedure

The camera-based systems used for the gait pattern analysis were a VICON MX-T10 (Vicon Motion Systems Ltd., Oxford, UK), which is the most widely used system, and a Raptor-E Digital Real Time System (Motion Analysis Corporation Inc., Santa Rosa, CA, USA). Among these two types of camera-based systems, VICON MX-T10 was used in hospitals A and C, while Raptor-E Digital Real Time System was used in hospital B. The IMU (35 mm×60 mm×25 mm)-based gait analysis system, Motion Track (R. Biotech Co. Ltd., Seoul, Korea), consisted of a gyroscope, an accelerometer, and magnetometer sensors.

A reflective marker-based 3D infrared camera system was simultaneously used to evaluate the validity of the IMU. The markers used to analyze the lower limb motion during gait were attached to the body using the plug-in-gait marker set method. The wearable wireless IMUs were attached to the dorsa of both feet, the shafts of both tibias, and the middles of both femurs, as well as the lower abdomen, and were affixed with stretch bands. As shown in Fig. 2, the IMU sensors were placed on a holder so as to increase stability and accuracy.

Signals from each sensor were received and collected using Bluetooth. The spatio-temporal (i.e., gait cycle time, stance, swing phase, velocity, and distance) and kinematic (i.e., hip, knee, and ankle angle in three dimensions) data were analyzed using MATLAB v2010a (MathWorks Inc., Natick, MA, USA). Prior to the actual measurements, each 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 refers to how well it matches the true value, but the true value of the gait does not currently exist in theory. In this study, the validity of the gait analysis was evaluated using the root mean square error (RMSE) of the parameters simultaneously obtained through the camera- and IMU-based systems. RMSE is widely used to verify the validity of gait analysis by analyzing the average difference between the parameters [12,22,23]. If the value of the RMSE is small, then the signals are close to each other. The reliability of the IMU was inspected using the intraclass correlation coefficient (ICC) of the spatio-temporal and kinematic parameters measured by the IMU in three different experimental settings with a certain time interval between each. In particular, the kinematic parameters were divided into 100 points according to gait cycle, and ICC was calculated by comparing the parameters at each point, respectively. ICC was calculated in SPSS version 21.0 (IBM SPSS, Armonk, NY, USA).

Attitude and heading reference system (AHRS) module

The inertial sensor-based AHRS was designed and developed. The AHRS could objectively measure the kinematic motions of each joint when attached to the body joints. In addition, the AHRS measured the directions of the gravitational and magnetic fields of the Earth [18].

The AHRS module was composed of an 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 was an integrated sensor (MPU9250; InvenSense, San Jose, CA, USA) composed of a gyroscope (range, ±2,000°/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 a frequency of 100 Hz in each signal. The collected angular velocity, acceleration, and magnetometer values were combined. The gradient descent algorithm was used to calculate the Euler angle, yaw, pitch, and roll of the AHRS module [18]. The calculated values were transmitted to a PC using a wireless Bluetooth module (PAN1321i; Panasonic, Osaka, Japan) [24].

The inaccurate measurement by the gyroscope of the angular velocity was supplemented, and the integrals were obtained in order to calculate and reliably determine the Euler angle based on the data from the magnetometer, which provided data on the Earth's magnetic field using the gradient descent algorithm [9], as well as the data from the accelerometer, which provided data on the gravity and inertia.

Gait event detection and temporal parameter calculation

The differential calculated from the Euler angle of the foot determined the gait event (Fig. 3). The gait temporal parameters were also obtained. Fig. 3 presents the algorithm used to determine the temporal parameters using a 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 [25].

The inertial sensor data based on the verified algorithm detected the heel strike (HS) and toe-off (TO) points [26].

The peak rotation rate is the maximum rotation rate of the ankle achieved during the swing phase [25-27]. The minimum value of the TO is the minimum value larger than the peak rotation value at mid-swing [25]. 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 [25].

The gait cycle was formed so as to calculate the gait temporal parameters after the HS and TO detections. The temporal parameters (i.e., swing phase [SW] and stance phase [ST]) can be calculated using Eqs. (1) and (2), respectively, based on these time events [26-28].

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

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

Spatial parameter calculation

In the spatial parameter calculation, the distance traveled by the subject was determined by the double integration of the momentary acceleration measurements. The position or distance values obtained by the integration were suitable only for a short term because of the drift error of the accelerometer [29]. In other words, the calculations of the velocity and the distance using the double integration of the acceleration measurements produced a relatively large accumulated error. These values should thus be measured after every step the pedestrian takes in order to avoid this accumulated error, as

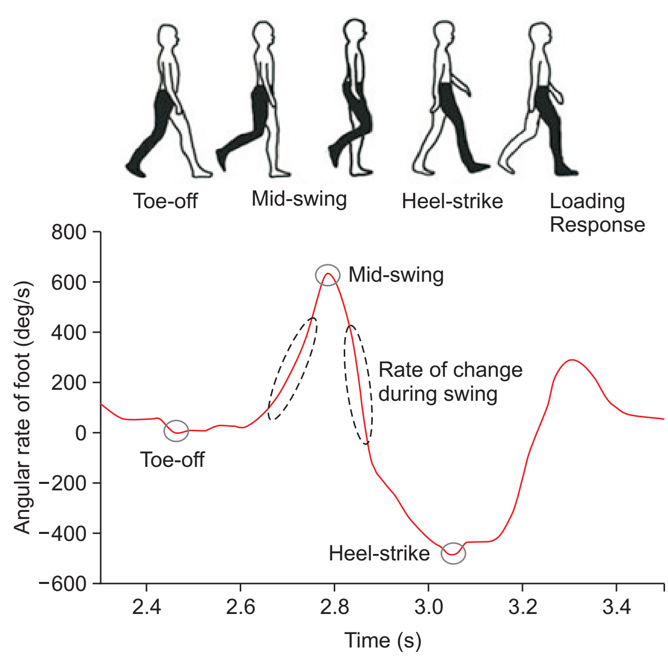

Fig. 3. The angle of rotation of the foot was used to determine the gait event through a gyroscope on the foot.

the successive measurements of speed and distance were not affected if the velocity and distance estimations were measured in each step. Therefore, the accumulated error of the AHRS was corrected in this way [29]. 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 the angular velocity from the AHRS modules [30].

The velocity and distance were calculated by double integrating the acceleration measurements. The gravitation influences and accumulated error were removed so as to calculate accurate values.

Calculation of joint angles

A total of seven AHRS system modules were attached to the participant's joints to measure the joint angles during the rehabilitation gait analysis. The modules were attached to the abdomen, bilateral femurs, bilateral tibias, and each of the feet using a stretch band. The angle joints were calculated using the Euler angles obtained from each joint. An algorithm to calculate the joint angles, which were an important biological measurement for rehabilitation, was also developed in this study [23,24].

Fig. 5 shows a conceptual map of the algorithm that calculates the joint angle in each segment; the 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.

Fig. 5 represents the tibia anatomical (TA) and the femur anatomical (FA). Each sensor axis was labeled as tibia measurement (TM) and femur measurement (FM). The conversion matrices T_{TATM}, which is a matrix wherein the sensor axis is converted to the tibial axis, and T_{TAFM}, which is a matrix wherein the sensor axis is converted to the femoral axis, were used to convert the axis of each sensor into one single axis. The ultimate matrix representing the joint angle between the two sensors is expressed in Eq. (3) [23].

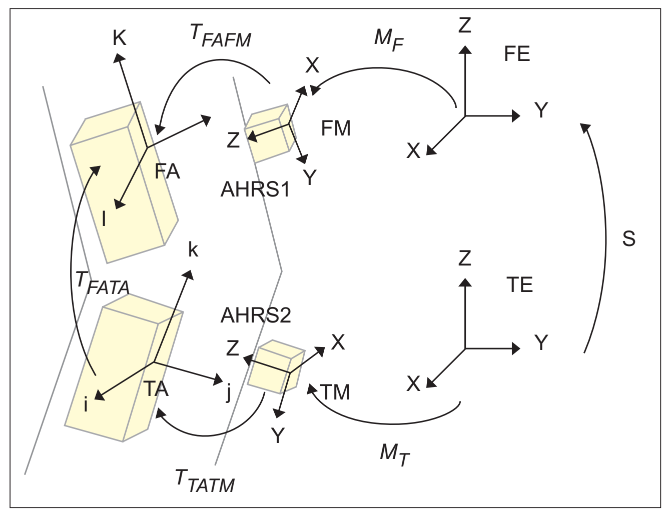

Fig. 5. A conceptual map presents the segmental joint angle calculation method in the knee joint as an example. The same algorithm can be applied to other segmental joint angles. AHRS, attitude and heading reference system; TA, tibia anatomical; TM, tibia measurement; FA, femur anatomical; FM, femur measurement.

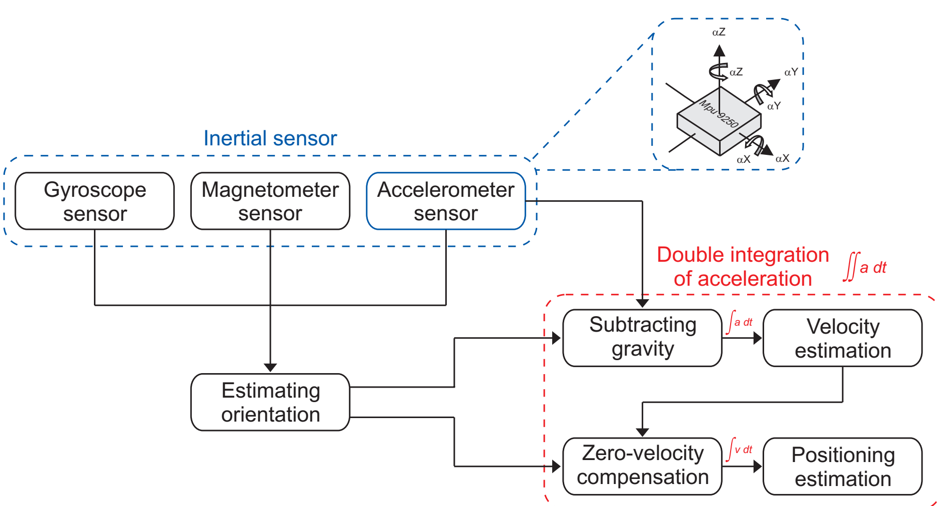

Fig. 4. A two-phase cumulative error reduction algorithm is used to minimize the accumulated error of the double integration, which was calculated using the acceleration values and the angular velocity from the attitude and heading reference system (AHRS) modules.

$$T_{FATA} = T_{FATM} M_F S M_T^{-1} T_{TATM}^{-1},$$
$$T_{FATM} = T_{TATM} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (3)$$

S represents the alignment matrix between two axis sensors of the earth (i.e., FA and TA), while M_F and M_T represent the directions of the femur and the tibia relative to the axis of the Earth, respectively. As shown in Eq. (3), the T_{FATA} matrix terms were used to calculate the joint angles: flexion/extension, abduction/adduction, and internal/external rotations.

$$\text{Flexion/Extension} = tan_2^{-1}\left(\frac{-T_{FATA}(2,3)}{T_{FATA}(3,3)}\right),$$
$$\text{Abduction/Adduction} = sin^{-1}(T_{FATA}(1.3)), \quad (4)$$
$$\text{Intercal/Extermal} = tan_2^{-1}\left(\frac{-T_{FATA}(1,2)}{T_{FATA}(1,1)}\right).$$

RESULTS

A camera-based system was used to simultaneously determine the validity of the IMU and measure the spatio-temporal and kinematic parameters of the three healthy participants in the three different hospital settings; the results of the IMU- and camera-based systems were then compared to each other. The spatio-temporal and kinematic parameters of the three healthy participants measured with the IMU in different hospitals were compared so as to evaluate the reliability of the IMU. In addition, the reliability of the camera-based system in the three different hospitals was evaluated for one healthy participant.

Validity (IMU- vs. camera-based system) of spatio-temporal and kinematic parameters

The segmental joint angles on both lower limbs were measured with seven AHRS system modules in order to evaluate the performance of the gait analysis system. The attachment locations were the abdomen, the bilateral femurs and tibias, and the feet. The joint angles were calculated with the joint angle calculation algorithm based on the Euler angle of each joint as provided by the individual modules. The Euler angles obtained from the AHRS in the segmental joints while the participant completed the 10-m gait course were used to calculate the joint angles. Ten trials were conducted so as to measure under identical protocols. Tables 1 and 2 show the inspection results between the two systems measured at the three hospitals.

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 as measured by the camera- and IMU-based systems in the three separate hospitals.

The velocity measured with the IMUs was in the range of 1.18–1.22 m/s, whereas that measured with the camera-based system was in the range of 1.23–1.30 m/s. The stride lengths measured with the IMU- and camera-based systems were in the ranges of 1.19–1.26 m and 1.21–1.29 m, respectively.

The stance phase (%) measured with the IMUs was in the range of 57%–58%, whereas that with the camera-

Table 1. Temporal and spatial parameters of the camera- and IMU-based systems obtained from the three separate hospitals

		Velocity (m/s)	Stride length (m)	Stance phase (%)	Swing phase (%)
National Rehabilitation Center	IMU	1.22±0.06	1.26±0.09	58±2.0	42±1.0
	Camera-based system	1.30±0.08	1.21±0.10	63±1.0	37±2.0
Veterans Health Service Medical Center	IMU	1.19±0.05	1.25±0.03	58±2.0	42±2.0
	Camera-based system	1.24±0.10	1.29±0.07	61±2.0	39±1.0
Yonsei University Hospital	IMU	1.18±0.08	1.19±0.12	57±3.0	43±2.0
	Camera-based system	1.23±0.11	1.24±0.03	61±1.0	39±1.0

Values are presented as mean±standard deviation.
IMU, inertial measurement unit.

Table 2. Kinematic parameters for the camera- and IMU-based systems obtained from the three hospitals

		RMSE		
		National Rehabilitation Center	Veterans Health Service Medical Center	Yonsei University Hospital
Sagittal	Hip joint angle	1.72	1.43	2.24
	Knee joint angle	2.77	2.57	2.71
	Ankle joint angle	1.73	2.36	1.53
Frontal	Hip joint angle	3.48	1.57	2.68
	Knee joint angle	1.77	2.13	2.28
	Ankle joint angle	1.39	1.81	1.65
Transverse	Hip joint angle	3.76	3.62	4.15
	Knee joint angle	2.89	3.11	2.95
	Ankle joint angle	2.78	3.36	4.37

IMU, inertial measurement unit; RMSE, root mean square error.

based system was in the range of 61%–63%. The swing phase (%) measured with the IMU- and camera-based systems were in the ranges of 42%–43% and 37%–39%, respectively. Overall, the values measured with the two systems did not show any remarkable differences.

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

The RMSE value of the ankle joint angle on the frontal plane was at its lowest at 1.39, while it it was at its highest at 4.37. The results verified the validity of the IMUs. Table 2 shows the RMSE values obtained at the hospitals.

Reliability (IMU- and camera-based systems) of spatio-temporal and kinematic parameters

The intra-rater and inter-rater reliabilities of the measurement results were examined using ICCs to verify their reliabilities. Therefore, an analytical method was used to evaluate the reliability of the IMU- and camera-based systems in order to verify the intra-rater and inter-rater reliabilities. The number of operators varied according to the task, and the experiment was conducted on three subjects in three hospitals.

Table 3. Intra-rater reliability of kinematic and spatio-temporal parameters (IMU-based system)

Variable	ICC
Kinematic parameters	
Hip flexion/extension	0.998
Hip adduction/abduction	0.988
Hip internal/external	0.980
Knee flexion/extension	0.998
Knee varus/valgus	0.884
Knee internal/external	0.946
Ankle dorsi/plantar flexion	0.967
Ankle inversion/eversion	0.912
Ankle internal/external rotation	0.953
Spatio-temporal parameters	
Stance phase (%)	0.894
Swing phase (%)	0.894
Velocity (m/s)	0.869
Stride length (m)	0.830

IMU, inertial measurement unit; ICC, intraclass correlation coefficient.

Intra-rater reliability (IMU-based system, n=3) of spatio-temporal and kinematic parameters

One operator performed a gait test to measure the reliability of the IMU-based system and obtain the spatio-temporal and kinematic parameters of the three subjects at the three hospitals measured on different dates. The results in Table 3 show that the ICC of the kinematic parameters ranged from 0.884 to 0.998, which was highly correlated with all of the parameters. The spatio-temporal parameters were very high as well (0.830–0.894) (Table 3).

Inter-rater reliability (IMU-based system, n=3) of spatio-temporal and kinematic parameters

Three operators performed a gait test to measure the reliability of the IMU-based system and obtain the spatio-temporal and kinematic parameters of the three subjects at the three hospitals measured on different dates.

According to the measured results, the ICC in the kinematic parameters ranged from 0.864 to 0.999, indicating a very high correlation for all of the parameters. The spatio-temporal parameters were very high as well (0.800–0.883) (Table 4).

Inter-rater reliability (camera-based system, n=1) of spatio-temporal and kinematic parameters

Operators working in the three different hospitals performed a gait test to verify the reliability of the camera-based system and record the spatio-temporal and kinematic parameters of the same subject.

As can be observed in Table 5, the ICC of the kinematic parameters was 0.368–0.996. The ICC for the hip internal/external showed a particularly low correlation of 0.368. The ICC of the spatio-temporal parameters ranged from 0.733 to 0.802 (Table 5).

DISCUSSION

Gait analysis is an important indicator that can determine the levels of progression of several diseases, such as musculoskeletal disease, cerebral palsy, Parkinson disease, and stroke. In addition, interest in gait analysis is increasing not only in non-patients, but also in youth and adolescents who are still in the growth phase. Therefore, accurate gait analysis is crucial to identify the characteristics and problems of gait and to estimate and maintain health. Furthermore, systematic and accurate gait analysis and gait data should be able to provide feedback on causal diseases. Gait correction could play an important role in terms of health maintenance and clinical diagnosis/evaluation.

To date, camera-based gait analysis along with OMC is widely used for gait analysis. However, camera-based systems are very expensive, and their maintenance is costly. In addition, their measurements can be easily influenced not only by the software version they are using, but also by the motion capture system, protocol, pathway length,

Table 4. Inter-rater reliability of kinematic and spatio-temporal parameters (IMU-based system)

Variable	ICC
Kinematic parameters	
Hip flexion/extension	0.995
Hip adduction/abduction	0.963
Hip internal/external	0.988
Knee flexion/extension	0.999
Knee varus/valgus	0.864
Knee internal/external	0.954
Ankle dorsi/plantar flexion	0.938
Ankle inversion/eversion	0.914
Ankle internal/external rotation	0.942
Spatio-temporal parameters	
Stance phase (%)	0.883
Swing phase (%)	0.883
Velocity (m/s)	0.882
Stride length (m)	0.800

IMU, inertial measurement unit; ICC, intraclass correlation coefficient.

Table 5. Reliability of kinematic and spatio-temporal parameters (camera-based system, n=1)

Variable	ICC
Kinematic parameters	
Hip flexion/extension	0.996
Hip adduction/abduction	0.960
Hip internal/external	0.368
Knee flexion/extension	0.989
Knee varus/valgus	0.810
Knee internal/external	0.609
Ankle dorsi/plantar flexion	0.987
Ankle inversion/eversion	0.688
Ankle internal/external rotation	0.659
Spatio-temporal parameters	
Stance phase (%)	0.802
Swing phase (%)	0.802
Velocity (m/s)	0.782
Stride length (m)	0.733

ICC, intraclass correlation coefficient.

marker set, and other experimental setting characteristics. The combination and configuration of different hardware and software can produce large discrepancies in camera-based gait analysis systems [10]. Therefore, there are problems associated with the validity and reliability of such results.

Therefore, it is essential to find solutions for these problems. Concomitant with the increased interest in gait analysis and awareness of its importance, inexpensive inertial sensor-based wearable gait measuring sensors that are easy to use and require less space are currently being developed.

In this study, multiple clinical gait measurements of three healthy subjects obtained in three different hospitals were compared. A number of previous studies examining devices for gait analysis have analyzed fewer than five gait trials of fewer than 10 subjects [26,31,32]. In one study that performed more than 10 gait trials, the inclines and speeds of the treadmill were different, but there was no repetition under the same conditions [28]. There was another study conducted on 19 subjects, but the number of trials per subject was only two [33]. Compared with the previous studies, ten trials of the gait of three subjects in three hospitals have sufficient statistical significance in this study.

Inertial sensors were used to measure the gait pattern without being restricted by space. The gait data obtained through the inertial sensor-based analyzers were compared to those obtained by a camera-based gait analysis system, and their validity was verified. Furthermore, the reliabilities of the different measurement results taken with different IMU-based systems were verified.

The validity of the IMU-based system was evaluated by comparing the measurements obtained to those from a camera-based system that was used simultaneously to measure the spatio-temporal and kinematic parameters.

The results of this study were similar to those obtained by Watanabe et al. [7], who reported that the stride length measurements taken with a wearable sensor system measuring spatio-temporal parameters showed a consistent measurement accuracy. This indicates that the system used here could be used effectively and practically for gait measurements.

Lutzner et al. [34] reported that the accuracy of an inertial sensor is the highest in the velocity range of 1.0–2.2 m/s (3.6–7.9 km/h) and lower at velocities both below 1.0 m/s and above 2.2 m/s. The participant's gait speed in this study was the self-selected speed at which the participant felt the most comfortable. The gait speed measured by the IMU system was in the range of 1.16–1.20 m/s, which was within the range of the accurate speed measurement. Therefore, the validity of the IMU based on the gait speed could be investigated in further studies by comparing them to camera-based systems.

The measurement results of the camera- and IMU-based systems sometimes showed a substantial difference because of the locations of the IMU attachments and magnetic waves. The discrepancies were produced during the calculation process with MATLAB. In this study, the lower limb joint angle measurements measured with the two systems were analyzed in order to inspect the accuracy of the IMU, which did not show any significant differences. The results indicated that the performances of the IMU-based systems were not inferior to the performances of the camera-based systems.

An IMU measures the kinematic values not via absolute coordinates, but by using acceleration, which is a relative value. Although inertial sensors are promising for applications in human motion detection, they could distort the kinematic data caused by the drift effect [31,35]. Therefore, as with other measurement sensors, the measurement accuracy of the IMU should be prioritized. Hamacher et al. [33] reported that a recalibration algorithm can be used to supplement the drawbacks of the system and thus increase the measurement accuracy.

Operators working in the three different hospitals performed a gait test so as to verify the reliability of the camera-based system and record the kinematic parameters of the same subject. The measurement results showed that the ICC was highly correlated in most kinematic parameters, while only that for hip internal/external was low at 0.368.

The discrepancies between the measurements taken with the camera-based systems in different experimental settings are typically larger in the hip, smaller in the ankle, and larger on transverse planes. Previous studies have indicated that these discrepancies are related to the estimation of the thigh segment pose [10].

The reliability verification process between the IMU-based systems in this study showed that although the same evaluator and the same participant conducted and completed all of the trials, respectively, small discrepancies were found between the measurements. Furthermore, although the same participant conducted all of the trials, the human gaits slightly differed in each occasion, which is not the case with machines. In addition, the discrepancies could corroborate the fact that the locations of the sensors are some of the most important causes of error in the inertial gait analysis [23].

The mechanical accuracy of IMUs could produce errors when measuring body movements, such as joint angle measurements. During the measurements of the acceleration and the angular velocity, the measurement plane of the IMU modules on the body did not mechanically coincide because of the curves on the body [32].

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 the kinematic parameters ranged from a minimum of 1.83 to a maximum of 3.98, with a tolerance close to 1%. The comparison results of the two systems indicated that IMU-based systems can replace camera-based systems [12,22,23]. The errors in the joint angles during the gait analysis were within the tolerance range, and these errors could be reduced by replacing the gyroscope, accelerometer, and magnetometer sensors with one integrated sensor. Therefore, the measurements taken by both systems were considered to be congruent.

The reliability levels were calculated using ICCs. In recent studies on gait analysis, ICC has been widely used for reliability verification [36,37]. In the reliability analysis, the ICC value, which is the coefficient of confidence, was ≥80, indicating a very high confidence level [38]. In this regard, the results of this study also showed that the reliability of the IMU-based system was confirmed, as all of the variables showed a statistically high ICC. Therefore, IMU-based systems are considered to be reliable for gait analysis. The spatio-temporal and kinematic parameters were measured as well. Consequently, the IMU-based system showed a higher ICC than the camera-based system. The ICC value of the camera-based system was low as a result of the difference in the position of the marker with respect to the subject, depending on the operator.

The limitations of this study include the fact that the study was conducted on three participants, and that 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 by investigating the validities and reliabilities of IMU-based systems for patients with abnormal gait.

This study verified the validity and the reliability of the IMU-based system. The results indicated that IMU-based systems can be widely used for rehabilitation and gait analysis in clinical settings. Accordingly, interaction-coaching systems must be developed so as 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 qualities of patients' lives, because the cost for gait analysis will decrease in the future.

In conclusion, an IMU-based system is inspected herein in order to verify its validity and potential to replace camera-based systems, which have limitations of high cost, complex procedures, and space restrictions. The results indicated that the IMU-based system can be effectively used in clinical settings and could be applied to other fields that require gait analysis. Furthermore, it is expected that such systems will come to be widely used in related fields. IMU-based systems provide accurate gait data in real time; hence, they can contribute to faster diagnosis and evaluation by physicians.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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