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The test-retest reliability of gait kinematic data measured using a portable gait analysis system in healthy adults

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Abstract

Background: Gait analysis is an important measurement for health professionals to assess gait patterns related to functional limitations due to neurological or orthopedic conditions. The purpose of this study was to investigate the reliability of the newly developed portable gait analysis system (PGAS).

Design: Cross-sectional design. Test-retest study.

Methods: The PGAS study was based on a wearable sensor, and measurement of gait kinematic parameters, such as gait velocity, cadence, step length and stride length, and joint angle (hip, knee, and ankle) in stance and swing phases. The results were compared with a motion capture system (MCS). Twenty healthy individuals were applied to the MCS and PGAS simultaneously during gait performance.

Results: The test-retest reliability of the PGAS showed good repeatability in gait parameters with mean intra-class correlation coefficients (ICCs) ranging from 0.840 to 0.992, and joint angles in stance and swing phase from 0.907 to 0.988. The acceptable test-retest ICC was observed for the gait parameters (0.809 to 0.961), and joint angles (0.800 to 0.977).

Conclusion: The results of this study indicated that the developed PGAS showed good grades of repeatability for gait kinematic data along with acceptable ICCs compared with the results from the MCS. The gait kinematic parameters in healthy subjects can be used as standard values for adopting this PGAS.

Key words: Gait analysis, Portable gait analysis system, Test-retest, Reliability

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Ⅰ. Introduction

Over the past centuries, gait analysis has evolved by integrating measurements, descriptions, and evaluations to analyze human locomotion characteristics and provide information on gait kinematic and kinetic for researchers and clinicians (Ghoussayni et al, 2004). Gait analysis provides a baseline for planning, evaluation, and management for patient treatment in the medical field, also is used in elderly healthy to provide a valuable information (Dobkin et al, 2004; Yavuzer et al, 2008).

Gait analysis systems have been developed with its various needs, among which, due to the accuracy of the equipment, motion analysis systems have become the gold standard today but, these motion analysis systems required expensive high-speed cameras, specialized internal motion analysis laboratories, and post-processing periods to obtain accurate data, therefore, it was necessary to develop alternative gait analysis equipment using wearable sensors such as the accelerometer, gyroscope, magneto-resistive sensors, flexible goniometer, electromagnetic tracking system (ETS), sensing fabric, force sensor, and sensors for electromyography to overcome the limitations of the laboratory environment and high price (Tao et al, 2012; Wagner and Ganz, 2012; Park et al., 2019).

In recent years, various gait analysis devices based on wearable sensors have been proposed, and meaningful progress has been made. The approach reported by the researchers includes a 3-axis acceleration and gyro sensor based on the Quaternion calculation method (Tadano et al, 2013), the body inertial sensing network (Guo et al, 2012), an accelerometer and magnetometer (Kun et al, 2011), an anatomical coordinate system using an intra-shoes pressure measurement system (IPM) (Kim and Nussbaum, 2014) and foot switches and micro-controller, connected to an Android Smart-phone using Bluetooth (Wagner and Ganz, 2012).

There are many commercial gait analysis systems based on wearable sensors, but similar devices are still being developed, which is proof of the lack of satisfaction with existing products. Moreover, for individuals in special circumstances, such as patients in the recovery phase of musculoskeletal or nervous system diseases, being able to simultaneously collect the gait analysis results in a free examination environment may provide useful information for measuring and evaluating gait to the treatment provider. In particular, for patients requiring intervention, the collection of spatio-temporal gait parameters without post-processing time is useful to immediately reflect the intervention after measurement (Lopez-Meyer et al, 2011).

Therefore, we proposed a new portable gait analysis system (PGAS) with simple post-processing time, user-friendly, and no experimental site restrictions. The primary goal of this study was to compare the tempo-spatial gait parameters of PGAS developed based on the wearable sensor and the motion capture system to confirm its reliability.

Ⅱ. Methods

1. Subjects

The test-retest study was used to examine the agreement between the same gait parameters such as gait velocity, cadence, step length, stride length, and joint angle (hip, knee, and ankle) obtained with PGAS and MCS. Twenty healthy subjects who had no history of neurological or musculoskeletal pathologies were recruited from the S University. All experimental protocols and procedures were explained to each subject and approved by the institutional review board of Sahmyook University. All subjects provided written informed consent prior to enrollment in this study.

2. Study protocol

A trained examiner explained the tasks through simple instructions before the experiment and leg length (from the great trochanter to the lateral epicondyle, from the lateral epicondyle to the heel through the lateral malleolus) was measured with tape measure. The measurement of the leg length is used for calculating the gait variable by inputting PGAS before the start of the experiment. Participants wore the sensors unit and reflective markers of both devices at the same time without overlapping them, and also walked 12m walkway along the blue line with the ready signals of the measuring administer of both devices. All subjects performed twice time with barefoot and allowed a break time on a chair between trials.

3. Experimental tool

1) Portable Gait Analysis System (PGAS)

The PGAS in this study consisted of eight three-dimensional (3D) inertial measurement unit (IMU) boards as wireless sensors, and one main board as a fusion center. Each IMU board consist of a magnetometer, an accelerometer, a gyroscope, and a Bluetooth transmitter and it can measure the absolute angle of the ankle, shank, thigh, and pelvis based on an axis perpendicular to the ground using a sensor attached to the body segment, and transmit the measured angle data to the main board (Kok et al, 2012). The fusion center receives the raw angle data via the Bluetooth receivers, the MCU of the fusion center combines the angle data of the hip, knee, and ankle, and transmits it to the computer connected by a universal asynchronous receiver and transmitter (UART) and to universal serial bus (USB) bridge.

2) Motion Capture System (MCS)

The motion capture system attaches a marker to a joint point of the human body and analyzes the motion by photographing it with an infrared camera. In this study, we used Qualisys Motion Capture System (Qualisys AB, Savedalen, Sweden, 2012) as the MCS, and the system's ICC (Intra-class Correlation Coefficient) is reported from 0.88 to 0.97 (Ghariba et al, 2011). The camera system was calibrated on every morning prior to experimental and system was tracked the position of reflective markers in the room and calculates the temporal and spatial gait parameters based on foot contact and foot off events with six infrared cameras recoding at 100 Hz. 'Track Manager' (Track Manager version 2.5, Qualisys, Sweden, 2012) processed and calculated temporal and spatial gait parameters of motion and force plate data and Visual 3D Basic' (C-Motion, USA, 2012) was used to digitally reconstruct the subject's lower body anatomy and calculated the angle-change for the test subject’s left and right hip, knee, and ankle joints. 'Visual 3D' was also used to calculate the force plate data (Eigster, 2010).

4. Measurements

The experiment was conducted as a test-retest and while a 12m walk, the subject maintained a static posture for 10 seconds required to correct the accelerometer gravity before walking, and analyzed after removing both the initial 2m for acceleration and the last 2m for deceleration. The spatial-temporal variables measured in the two systems, such as walking speed, cadence, stride length, stride length, and joint angle, were used to compare the reliability of the two instruments.

5. Data analysis

SPSS version 20 statistical software (IBM, Chicago, IL, USA) was used for all statistical analyses. Results are presented as mean ± standard deviation. The Shapiro-Wilk test was used to analyze the normality of the distribution in the clinical and general characteristics of subjects. The test-retest reliability for each test within the PGAS and intra-tester reliability for each test between the PGAS and the MCS for all tempo-spatial gait parameters were estimated using the ICCs. For all test, statistical significance was set at 0.05.

Ⅲ. Results

For general characteristics of subjects, gender, age, height, weight, and leg length were checked <Table 1>.

Table 1. General characteristics of subjects (*N*=20)

Variables		M ± SD
Gender		male
Age (years)		26.15±4.68[a]
Height (cm)		176.15±4.81
Weight (kg)		69.25±8.15
Leg length (Rt)	Thigh	41.28±2.59
	Shank	49.48±2.61
Leg length (Lt)	Thigh	41.35±2.56
	Shank	49.68±2.36

[a]M±SD

The ICCs for each test within the PGAS were found to have good test-retest reliability in gait parameters (0.840 to 0.992) and joint ranges in the stance phase (0.907 to 0.988) and swing phase (0.909 to 0.982) <Table 2 and 3>.

Table 2. Test-retest reliability of the PGAS for gait parameters (*N*=20)

	Test	Reset	ICC	95% confidence interval	
				MIN	MAX
Velocity (m/sec)	1.081±0.208[a]	1.064±0.215	0.973	0.931	0.989
Cadence (step/min)	104±13.790	105±14.511	0.992	0.970	0.997
Rt step length (m)	0.612±0.064	0.612±0.060	0.975	0.936	0.990
Lt. step length (m)	0.615±0.064	0.603±0.056	0.910	0.772	0.964
Stride length (m)	1.216±0.114	1.227±0.114	0.974	0.933	0.99
Rt. stance (%)	60.633±3.023	61.000±2.256	0.840	0.597	0.937
Lt. swing (%)	39.367±3.023	38.999±2.258	0.841	0.597	0.937
Rt. stance (%)	60.988±2.569	60.596±2.791	0.962	0.903	0.985
Lt. swing (%)	39.012±2.569	39.403±2.791	0.962	0.903	0.985

[a] M±SD, PGAS=portable gait analysis system; Rt=right; Lt=left

Table 3. Test-retest reliability of the PGAS for joint angles of stance and swing phase (*N*=20)

		TEST	RESET	ICC	95% confidence interval	
					MIN	MAX
Stance phase	Rt hip (degree)	36.882±4.091[a]	37.114±3.997	0.988	0.970	0.995
	Lt hip (degree)	37.687±4.271	37.219±4.271	0.972	0.929	0.989
	Rt knee (degree)	34.439±2.980	35.273±2.567	0.962	0.904	0.985
	Lt knee (degree)	33.384±2.977	33.966±3.280	0.960	0.899	0.984
	Rt ankle (degree)	21.672±2.538	21.382±1.950	0.918	0.792	0.967
	Lt ankle (degree)	22.985±2.071	21.672±2.587	0.907	0.765	0.963
Swing phase	Rt hip (degree)	32.773±4.826	33.265±4.398	0.982	0.954	0.993
	Lt hip (degree)	31.624±4.876	33.394±4.647	0.924	0.809	0.970
	Rt knee (degree)	57.468±3.671	57.926±3.191	0.946	0.864	0.979
	Lt knee (degree)	57.043±4.713	57.353±3.336	0.909	0.771	0.964
	Rt ankle (degree)	18.868±3.393	19.190±2.714	0.953	0.882	0.981
	Lt ankle (degree)	19.688±4.624	20.058±3.928	0.943	0.857	0.978

[a] M±SD, PGAS=portable gait analysis system; MCS=motion capture system; Rt=right; Lt=left

The ICCs for each test between systems were found to have acceptable intra-tester reliability in gait parameters (0.809 to 0.961) and joint angles in the stance phase (0.800 to 0.977) and swing phase (0.817 to 0.942) <Table 4 and 5>.

Table 4. ICCs for gait parameters between systems (N=20)

		PGAS	MCS	ICC	95% confidence interval	
					MIN	MAX
Velocity (m/sec)	Test	1.081±0.209[a]	1.057±0.134	0.911	0.776	0.965
	Retest	1.064±0.215	1.076±0.179	0.886	0.712	0.955
Cadence (step/min)	Test	104.833±13.790	102.010±10.417	0.869	0.67	0.948
	Retest	105.444±14.511	104.17±9.181	0.833	0.577	0.934
Rt step length (m)	Test	0.612±0.060	0.614±0.065	0.842	0.601	0.937
	Retest	0.612±0.064	0.613±0.066	0.884	0.708	0.954
Lt. step length (m)	Test	0.603±0.056	0.620±0.059	0.809	0.517	0.924
	Retest	0.615±0.063	0.619±0.058	0.876	0.687	0.951
Stride length (m)	Test	1.215±0.114	1.234±0.121	0.861	0.649	0.945
	Retest	1.227±0.123	1.233±0.111	0.939	0.846	0.976
Rt. stance (%)	Test	60.633±3.023	60.259±2.800	0.811	0.522	0.925
	Retest	61.000±2.256	61.371±2.258	0.812	0.526	0.926
Lt. swing (%)	Test	39.367±3.023	39.741±2.800	0.811	0.522	0.925
	Retest	38.999±2.257	38.628±2.258	0.812	0.526	0.926
Rt. stance (%)	Test	60.988±2.569	61.377±2.745	0.961	0.901	0.999
	Retest	60.596±2.791	61.411±3.639	0.906	0.763	0.963
Lt. swing (%)	Test	39.012±2.569	38.623±2.745	0.961	0.901	0.985
	Retest	39.404±2.791	38.589±3.639	0.906	0.763	0.963

[a]M±SD, PGAS=portable gait analysis system; MCS=motion capture system; Rt=right; Lt=left

Ⅳ. **Discussion**

We have demonstrated that the reliability for measured tempo-spatial gait parameters such as velocity, cadence, step length, stride length, and angle in joint (ankle, hip, and knee) of healthy subjects, using a newly developed PGAS. As a result, the ICC for each test within the developed PGAS showed strong agreement on measurement repeatability and acceptable reliability compared to the MCS.

In a similar approach, Tadano et al (2013) suggested the implementation of wearable tri-axial acceleration and gyro sensors attached to a segment of the lower limbs, and estimated the angular velocity data during gait in five healthy individuals. The joint trajectory was in the horizontal and sagittal planes, and a comparison of this system was performed with a camera-based motion analysis system, with average root mean square error (RMSE) and correlation coefficient (CC) of 10.14° and 0.98 for the hip flexion, 7.88° and 0.97 for the knee flexion, and 9.75° and 0.78 for the ankle flexion angles. As a result, the RMSE represented a variation; however, with the high CC observed, researchers proposed that this was caused by inaccuracies in calculating the measurements from the camera images.

In this study, the sensor units were constructed with the tri-axial acceleration and gyro sensors as in the previous study; however, it could measure each joint angle and gait parameter such as velocity, cadence, step length, and stride

Table 5. ICCs for joint angles of stance and swing phase between systems (*N*=20)

			PGAS	MCS	ICC	95% confidence interval	
						MIN	MAX
Stance phase	Rt hip (degree)	Test	36.883±4.091[a]	36.379±4.068	0.977	0.941	0.991
		Retest	37.113±3.997	37.634±3.281	0.943	0.855	0.977
	Lt hip (degree)	Test	37.687±3.489	36.679±3.990	0.890	0.721	0.956
		Retest	37.219±4.271	36.679±3.772	0.836	0.585	0.935
	Rt knee (degree)	Test	34.439±2.980	33.450±3.610	0.821	0.548	0.929
		Retest	35.273±2.567	34.324±3.664	0.842	0.600	0.937
	Lt knee (degree)	Test	33.384±2.977	34.388±2.553	0.888	0.718	0.956
		Retest	33.966±3.280	35.525±2.710	0.899	0.744	0.960
	Rt ankle (degree)	Test	21.672±2.538	22.368±2.154	0.833	0.578	0.934
		Retest	21.382±1.950	22.154±2.261	0.856	0.635	0.943
	Lt ankle (degree)	Test	22.985±2.071	21.492±1.762	0.870	0.671	0.948
		Retest	21.672±2.587	22.576±1.784	0.800	0.495	0.921
Swing phase	Rt hip (degree)	Test	32.773±4.826	31.999±5.593	0.942	0.853	0.977
		Retest	33.265±4.398	31.874±4.266	0.863	0.654	0.946
	Lt hip (degree)	Test	31.624±4.876	32.483±6.129	0.884	0.708	0.954
		Retest	33.394±4.647	31.243±4.609	0.871	0.675	0.949
	Rt knee (degree)	Test	57.468±3.671	57.430±3.350	0.890	0.721	0.956
		Retest	57.926±3.191	58.062±4.398	0.835	0.583	0.935
	Lt knee (degree)	Test	57.043±56.252	56.252±4.915	0.890	0.722	0.956
		Retest	57.353±3.336	57.314±5.927	0.863	0.655	0.946
	Rt ankle (degree)	Test	18.868±3.393	19.259±3.909	0.872	0.676	0.949
		Retest	19.190±2.714	18.069±3.495	0.933	0.831	0.973
	Lt ankle (degree)	Test	19.688±4.624	19.594±4.667	0.939	0.846	0.976
		Retest	20.058±3.928	19.433±4.695	0.817	0.537	0.927

[a] M±SD, PGAS=portable gait analysis system; MCS=motion capture system; Rt=right; Lt=left

length simultaneously, and showed good ICCs compared with the MCS.

The body inertial-sensing network, which consisted of one three-axis accelerometer, one three-axis magnetometer, and one three-axis gyroscope, was tested by Guo et al (2012) and seven hemiplegia patients and seven healthy subjects were participated but only calculated the angle of knee flexion and extension in one gait cycle and then the researchers were considering other parameters such as the step length or hip joint angle in their future works. One of the advantages of PGAS developed compared to previous studies is that it can detect the sequence of gait cycles from the beginning to the end, and it is more appropriate for the analysis of the entire gait cycle to understand the variability during gait.

Lopez-Meyer et al (2011) used a wearable footwear-based sensor system like a Force-Sensitive Resister (FSR) and accelerometer to describe the temporal gait parameters of seven individuals with stroke and sixteen healthy subjects. This system automatically detected heel-strike and toe-off events, obtained temporal gait parameters as compared to the GAITRite system, and showed no significant difference in the cadence (p>0.35) and temporal gait parameters (p>0.18) in healthy subjects compared with the cadence (p>0.29) and temporal gait parameters (p>0.51) in subjects with stroke. As discussed, this method using FRS sensors only estimated cadence and temporal gait parameters. The present study focused on the accurate estimation of spatial and temporal parameters like velocity, walked distance, and joint angles of a subject by using data calculated from the accelerometer and gyro sensors. However, automatic detection of gait event is one of the strengths of wearable footwear-based sensor system; therefore, we also consider supplementation of FRS sensors in our future study.

Although decisive and excellent reliability were found in both test-retest reliability of a PGAS and intra-tester reliability of the two systems, the ICC for the ankle joint was lower than that for other joints in healthy subjects during gait. This indicated that there was a possibility of errors in the MCS or the PGAS. According to many researchers, even though Vicon motion analysis systems are referred to as the “Gold standard” for 3-D motion tracking system, they also have been reported an accuracy errors (Dorociak and Cuddeford, 1995; Windolf et al, 2008). The gait analysis system using a wearable sensor has also limitations such as attachment problems with strap and external signal noise (Tadano et al, 2013).

Regarding future studies on system implementation, several items could be considered for improvement. First, even though errors are very small, considering both a roll and a pitch can result in more precise stride or step lengths since a pitch can never be zero when patients walk. Second, since it seems that joint angles, especially angles of ankle, change faster than the 100 ms sampling speed, the sampling rate should be increased to, for example, 1 ms or 10 ms by adjusting the spaces of the Bluetooth devices due to the interference among them. Third, mechanical noises have been noticed owing to the body vibration when subjects walk. Therefore, since the phenomenon happens more with bigger or taller devices, smaller IMU devices with small batteries is preferred. Fourth, since the system provides only joint angles and step lengths, researchers use Excel to calculate stride lengths, cadences, velocities, and stance or swing durations. Instead, analytical tools could be embedded in the system, so that researchers can obtain the desired data easily. During experiments, researchers have to recharge the IMU devices from time to time, which means a low power design or high capacity batteries would be beneficial for researchers.

Ⅴ. Conclusion

The results of this study indicated that the developed PGAS showed acceptable agreement compared with the MCS, high test-retest reliability within the PGAS for dynamic gait analysis, and good grade of ICCs compared to the results from the MCS statistically. The gait kinematic parameters in healthy subjects can be used as standard values for using this PGAS.

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