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Research Article

Validation of a Synchronized Smartphone-Based Gait Analysis System

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Abstract

Background: Current smartphones are able to capture high quality videos, which have been used to measure movements such as gait and rhythm. Since the use of a single smartphone has several limitations, we propose a simple custom-built gait analysis system using three synchronized smartphones.

Methods: Walking of the healthy participants was recorded simultaneously with the proposed custom-built and the commercially available system. Static images from the captured videos were used for analysis of the temporal (stride time, stance time, double stance time, and swing time) and length (stride length and step length) parameters of the gait cycle. Three examiners evaluated the images separately, and the means of the results represented each index in our system.

Results: Values for all temporal and length parameters obtained from the custom-built and the commercially available gait analysis system were not significantly different. This supports the validity of our system. Inter- and intra-rater evaluation showed moderate to excellent agreement for all parameters.

Our system demonstrated satisfactory interchangeability with it, underestimating the stride time and swing time and overestimating stance time, double stance time, stride length and step length by an average measurement lower than 0.049 (sec), or 0.57 (cm) respectively.

Conclusion: The proposed custom-built gait analysis system may be a reliable alternative to the commercially available system. The simplicity and functionality of the custom-built system is applicable to almost all hospital settings and would be beneficial for the evaluation of gait in postoperative patients.

Keywords: *Gait Analysis; Smartphone; Correlation; Direct Linear Transformation*

Introduction

Since the early 2000s, custom-built motion capture systems were used to measure direct activity, such as gait and rhythm movements, by analyzing synchronized high-quality videos [1]. Entomologists and zoologists have also established synchronized video systems capturing motion of insect and animal legs where images are assembled into videos for evaluation. However, the system was expensive and the digitizing process time consuming [2].

In the field of Orthopedics, there are several methods used to analyze postoperative gait for the evaluation of treatment effectiveness. More recent technology using comprehensive three-dimensional motion capture systems and electronic walkways has demonstrated significant validity and reliability with regards assessment of spatiotemporal gait parameters [3,4]. These systems produce accurate outcomes with minimal bias enabling researchers to establish a reasonable framework for postoperative functional measurements. However, these systems require specialized equipment that may be too costly for use in regular clinical settings, especially in developing countries, and the use of these systems may be challenging for many clinicians. In addition, the system has to be installed in a designated room where assessment of other conditions, such as outdoor activities, cannot be achieved. Likewise, the use of another gait analyzer, an electronic walkway or a treadmill, may restrict the subject's movement within the relatively narrow width of the test field, which may in turn affect natural gait and rhythm [5].

Single video evaluation does not provide accurate gait analysis, especially for length and angle-related indices [6-9], and may lead to measurement errors, particularly regarding perspective distance [1]. Furthermore, a single sagittal video is devoid of three-dimensional (3D) orientation, lacking information from the frontal and rotational planes [10]. Several articles noted a great discrepancy in data obtained by a single camera system compared with a commercialized gait analyzing system, which was assumed to be due to noise or limited image resolution [9-12]. Moreover, images from single video recordings may be distorted, especially at the marginal regions of view, due to the property of the camera lens [13]. In general, it is difficult for any examiners to set a camera perfectly in the vertical position, without any degree of tilting.

Current smartphones are able to capture two-dimensional (2D) images whose image quality is much higher than images taken from phones of more than a decade ago [14]. In this article, we used three divergently positioned smartphones that recorded synchronized videos in the sagittal and 45-degree oblique planes, which allowed for construction of 3D dynamics, even in the perspective orientation. With this system calibration of distorted marginal views and data from inclined camera setting could be easily achieved. For an evaluating system to be widely accepted as a standard, it should be precise, objective, easy to handle, and cost-effective.

Aim of the Study

The aim of this article is firstly to introduce a simple custom-built smartphone-based system, and secondly to evaluate the comparative validity of data obtained from this system against a commercially available gait analysis system. We also evaluated the inter- and intra-rater reliability of spatiotemporal gait parameters. We hypothesize that gait indices of time-related factors, such as stance phase and swing phase, as well as length of stride and step would agree significantly with the commercially available gait analysis system.

Methods

Participants

Ten healthy individuals (5 men and 5 women) voluntarily consented to gait analysis testing. The mean age was 40 years (25 to 59 years), mean height was 160.6 cm (155 to 170 cm), and mean body weight was 57.5 kg (40 to 68 kg). All participants enrolled in this study met the following inclusion criteria: (1) age over 20 years, (2) no serious congenital disease or history of major trauma, and no neurovascular disorder of the lower extremities. The study was approved by the Regional Ethical Review Committee of the Nishi Hospital in Kobe City, Japan (#2019-01).

Measurement system: Walkway and smartphone set-up

To validate our custom-built system, gait of ten healthy individuals were simultaneously recorded with the commercially available gait analyzing system "Walkway MW-1000, Anima Corp, Tokyo, Japan" [15]. The walkway was approximately 6 meters in length, encompassing a calibrated space of 140 cm in length, 33 cm in width, and 80 cm in height. This would substantially cover the required 130 cm length of a standard walkway for accurate spatial resolution with a stationary camera set-up [6]. For calibration purposes, a rectangular paralleled-equipment (a 'utility rack') with 40 designated calibration points was set at an area corresponding to the center of the walkway (Figure 1). The center of the walkway was marked using a virtual orthogonal 3D coordinate system wherein the x-axis ran along the walkway (coronal view), the y-axis indicating vertically upwards, and the z-axis directed perpendicular to the walkway (sagittal view) (Figure 2a).

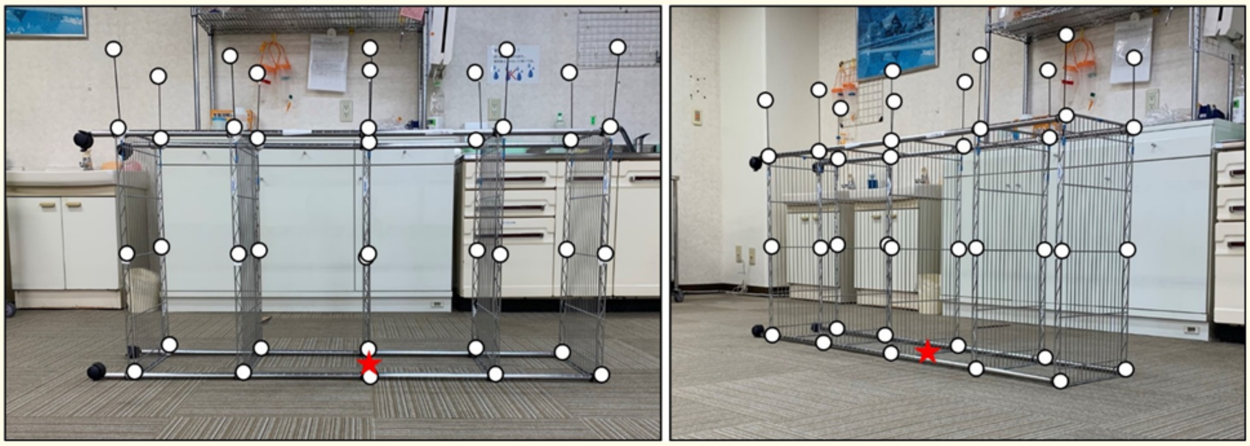

Figure 1: *Walkway Set-up showing the 'utility rack' in the center of the walkway in red star. Forty calibration points with known values reinforce measurement accuracy. Left: lateral, Right: 45-degrees oblique planes.*

Our custom-built gait analysis system consisted of three smartphones (iPhone 7, 8 and X, Apple USA Inc., Cupertino, CA) individually attached to tripods 40 - 50 cm above floor level, approximating the height of the knees of each participant (Figure 2b). The first smartphone was set in the sagittal plane (z-axis), the second smartphone along the coronal plane (x-axis), and the third smartphone in a 45-degree anterior lateral plane (between the sagittal and coronal planes). It was unnecessary to re-adjust the position of the smartphones, as image distortion could be calibrated by the Direct Linear Transformation (DLT) method, as detailed below.

The commercially available gait analysis system consisted of a sheet 2.4m in length and 0.6m in width ("Walkway MW-1000). The sheet was spread out on the walkway mentioned above. Similarly, a 'utility rack' was positioned on the center of the sheet.

Video recording

The next several subheadings are mainly described to explain for our system. Videos were recorded sequentially, beginning with the 'utility rack', followed by a tennis ball dropped by the examiner from shoulder height, which would be used for time synchronization of all recorded videos. Walking of the participant on the walkway was then initiated, until the participant walked back to the starting position. All participants were instructed to walk naturally at a normal and comfortable speed, wearing shirts and pants that are not too tight, nor too loose to affect identification and movement of body parts. Although the walkway extended to 6 meters, only the recorded videos from the central third of walking on the walkway were used for evaluation so as to lessen the effect of acceleration and deceleration. To assess for angle parameters, selected landmarks of bony prominences were marked by double-sided reflective adhesive tapes (Figure 2a and 2b). This marking process was not utilized in gait analysis for time and length.

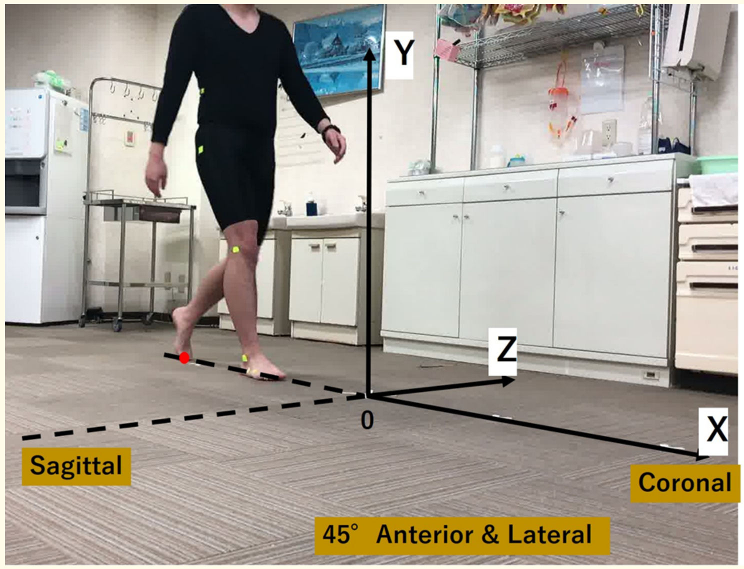

Figure 2a

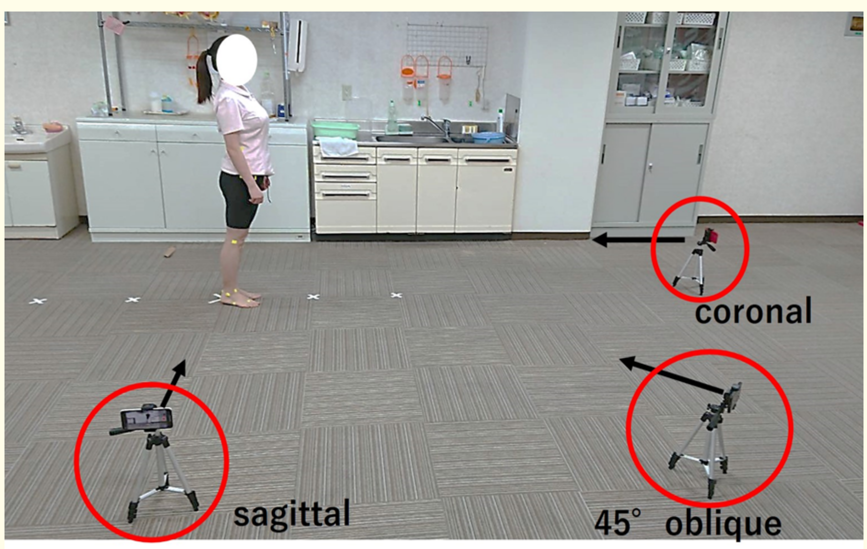

Figure 2b

Figure 1: *Walkway Set-up showing the 'utility rack' in the center of the walkway in red star. Forty calibration points with known values reinforce measurement accuracy. Left: lateral, Right: 45-degrees oblique planes.*

Analysis of images recorded with the custom-built system

Static images of all recorded videos from our custom-built system were selected and analyzed by three independent examiners (a senior surgeon, a physical therapist, and a medical social worker). All data were evaluated by the same examiners. The mean values for temporal and length parameters represented each index.

Temporal gait parameters

The temporal gait parameters included stride time, stance time, swing time, and double stance time. Each video recording (120 fps: frequency per second) was converted from the original format into stacks of static JPEG images. The sagittal static images of initial contact (IC) (heel) and toe-off (TO) of both feet were used to determine the temporal index of the gait cycle [11,12,16,17]. Initial contact was defined as the instance the foot contacted the floor, while toe off as the instance the foot left the floor [6]. Stride time was defined as the duration of a gait cycle. For each leg, a gait cycle consisted of two phases: stance time (duration from IC to TO) and swing time, known as leg swinging forward (duration from TO to the next IC) [6,16]. Double stance time was calculated from the IC and TO, with both feet in contact with the ground.

Time points of IC and TO from consecutive static images were visually determined by the three examiners mentioned above. Obtained data were exported to Microsoft Excel spreadsheets (Microsoft Corporation, Washington, USA) for computation of the temporal gait parameters.

Length gait parameters

Recordings of several steps were used to calculate for length parameters, namely stride length (the distance between 2 successive points of contact of a limb of the same foot), and step length (the distance between the first point of contact of a limb to that of the opposite limb). Recordings from the sagittal and oblique views were converted from the original format into stacks of static JPEG images for 3D dynamics. Static images of the 'utility rack' were used for calibration. For synchronization purposes the walking phase sequence from each camera image was matched with the instance the dropped tennis ball hit the floor. After image synchronization was done, consecutive matching of all images was completed from images taken at the same temporal interval. The matched static images from the sagittal and oblique views were then exported into ImageJ Software (National Institute of Health, Bethesda, MD, USA).

Direct linear transformation (DLT) method

DLT is a method used to determine the 3D location of points on an object using two or three images of the said object. The 3D position of interest could be calculated by mathematical 'triangulation' and 'matrix', since 2D image points refer to the same 3D object. The DLT method can also adjust for values from images affected by lens distortion or tilting based on known 3D calibration points [6,18]. The object or region of interest should be within the calibration points, determined from the corners of a rigid frame. A detailed mathematical explanation of DLT method is the beyond the scope of this article [19].

In this study, values of 3D coordinates for the tip of great toes was obtained, so that stride length and step length can be calculated from the difference between the x values (on the walkway) of the great toes ipsilaterally and contralaterally, respectively (Figure 3).

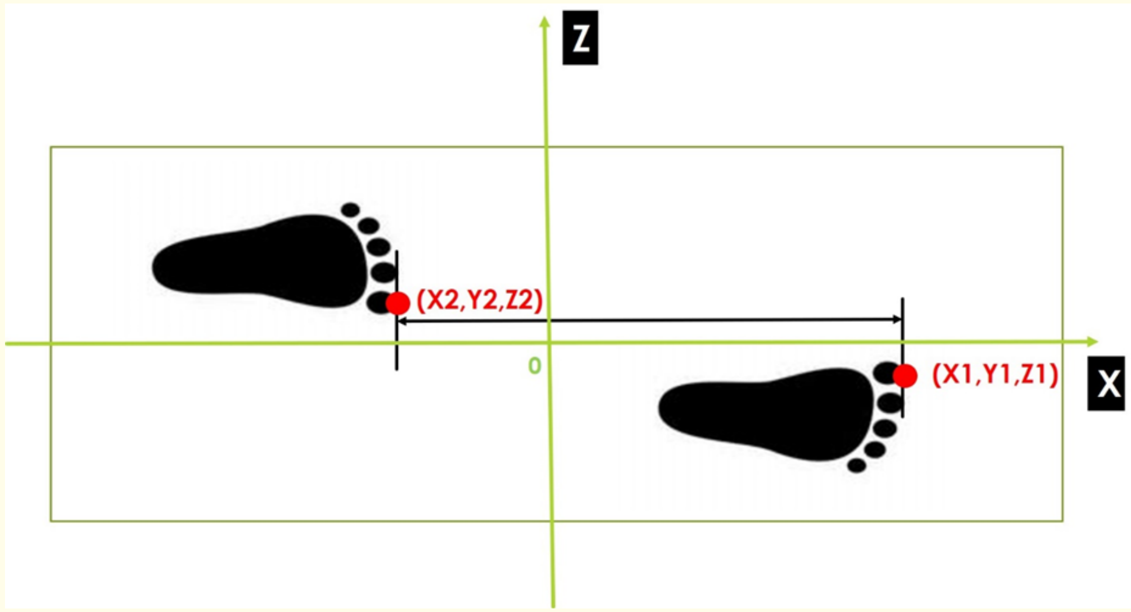

Figure 3: *Representative figure of bilateral footprints showing the tips of the great toes (red circles). Step length is calculated as difference of X values of 3D coordinates (X1-X2).*

Statistical analysis

Results from our custom-built system were compared with results from the commercially available gait analysis system. Bland-Altman analysis for time and length-related parameters was used to compare the difference between measurements from our custom-built system against the commercially available gait analysis system [20]. The mean measurement difference was used for over- or underestimation. The standard deviation (SD) expressed the extent of the difference. Scatterplots were used to show systematic bias [21].

Inter- and intra-rater reliability of 3 different observers was assessed by intraclass correlation coefficient (ICC). A single observer analyzed the same data at two different occasions, approximately ten days apart, to negate possible memory of the initial measurement. Normal distribution was determined by the Kolmogorov-Smirnov test, expressed with a 95% confidential interval (CI) and a P value. The strength of the correlation (r) was interpreted as either poor (< 0.5), moderate (0.5 to 0.75), good (0.75 to 0.9), or excellent (0.9<) [22].

All data were analyzed using the EZR software (Easy R, Saitama Medical Center, Jichi Medical University, Saitama, Japan).

Results

Measurement of gait parameters

Mean and SD values for all temporal and length gait parameters calculated from our custom-built and the commercially available gait analysis system did not show any significant difference, as shown in table 1.

	Current Method	Commercialized System
Stride Time (Sec)	1.07 ± 0.06 (0.99~1.14)	1.08 ± 0.06 (0.99~1.20)
Stance Time (Sec)	0.68 ± 0.05 (0.62~0.79)	0.67 ± 0.05 (0.60~0.76)
Swing Time (Sec)	0.38 ± 0.02 (0.36~0.43)	0.40 ± 0.02 (0.38~0.46)
Double Stance Time (Sec)	0.31 ± 0.04 (0.24~0.37)	0.27 ± 0.05 (0.2~0.39)
Stride Length (cm)	113.8 ± 11.2 (101.0~142.5)	113.5 ± 11.0 (100.5~142.0)
Step Length(cm)	57.5 ± 6.7 (48.9~73.7)	57.2 ± 3.1 (49.5~72.5)

Table 1: *Comparison of gait parameter values of custom-built vs commercially available system.*
Average ± SD (minimum~maximum).

Measurement of reliability

Comparing our values with those from the commercialized system, there was underestimation of stride time and swing time and overestimation of stance time, double stance time, stride length and step length by an average difference (± SD) of 0.007 sec ± 0.013 sec, 0.024 sec ± 0.017 sec, 0.023 sec ± 0.019 sec, 0.049 sec ± 0.033 sec, 0.59 cm ± 0.98 cm and 0.26 cm ± 0.84 cm; respectively (Figure 4a-4f). The SD values for all parameters did not show a significant percentage error between the two systems, indicating satisfactory agreement. Scatterplots did not show any improvement in agreement, regardless of measurements values.

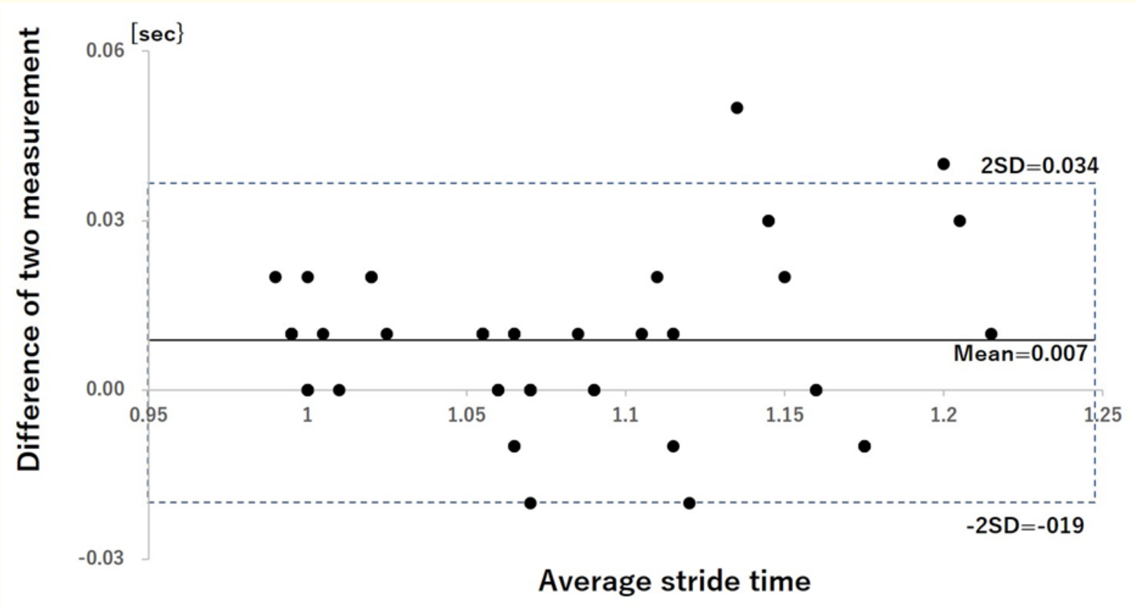

Figure 4a

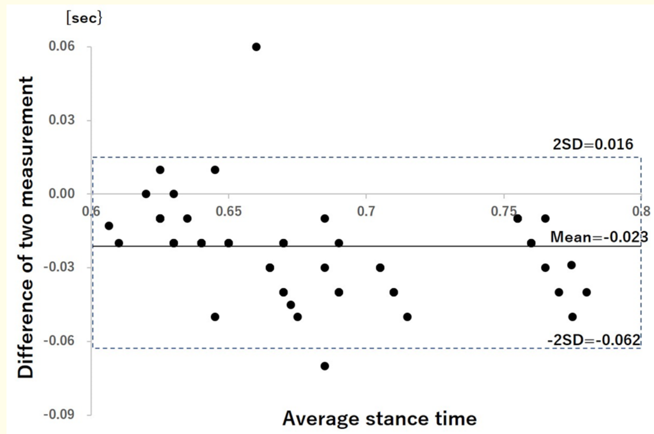

Figure 4b

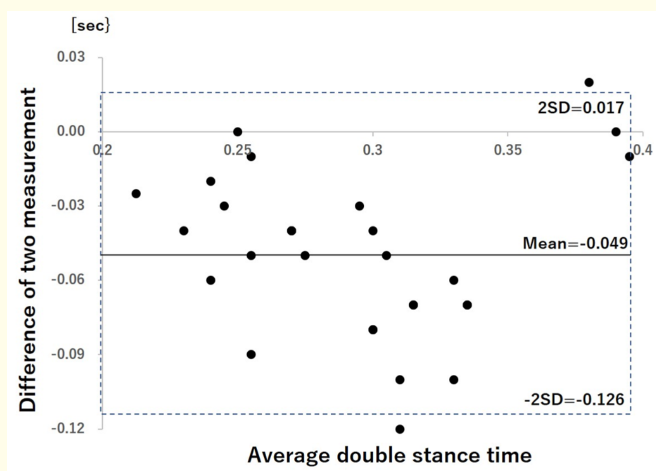

Figure 4c

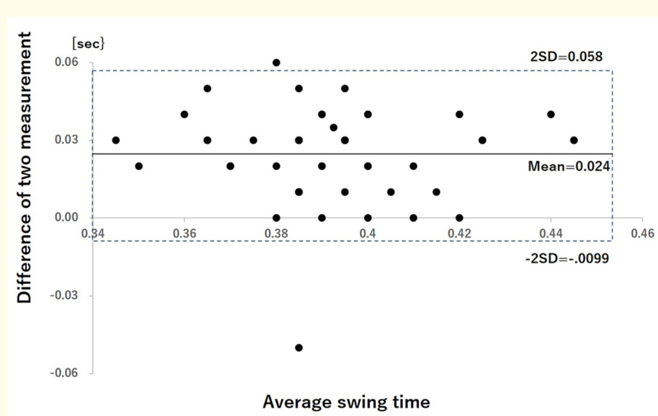

Figure 4d

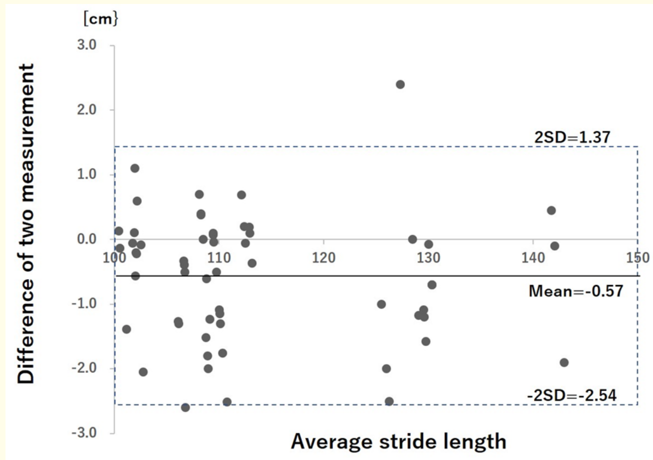

Figure 4e

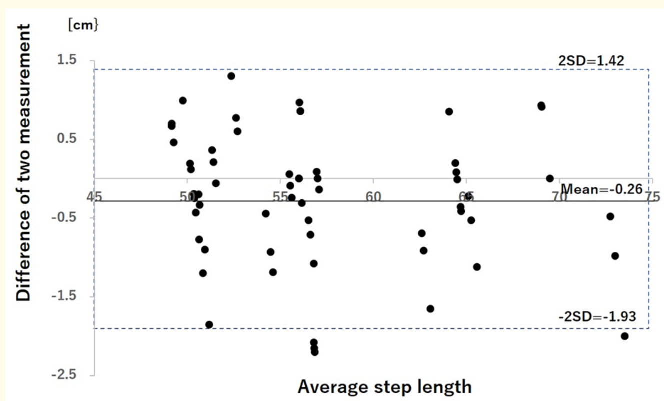

Figure 4f

Figure 4: *(A: Stride time, B: Stance time, C: Double stance time, D: Swing time, E: Stride length and F: Step length): Bland-Altman plots for gait parameters between the two systems. The horizontal axis represents the averages for each measurement and the vertical axis shows the differences. The two dotted lines indicate 95% confidence limits. All graphs show excellent agreement between the two measuring systems.*

Inter- and intra-rater reliability

The ICC values for inter- and intra-rater reliability for time and length-related parameters are shown in table 2a and 2b. Inter-rater reliability for stride time, stance time, step length, and stride length were in excellent agreement between the 3 observers (ICC ≥ 0.92, lower limit of 95% CIs ≥ 0.842, P < 0.001); good agreement in double stance time (ICC 0.762 and 95% CI 0.477 - 0.927, P < 0.05); and moderate agreement in swing time (ICC 0.509 and 95% CI 0.237 - 0.746, P = 0.069). Intra-rater reliability was excellent for stride time, stance time, double stance time, stride length, and step length (ICC ≥ 0.933, lower limit of 95% CIs ≥ 0.736), and moderate for swing time (ICC 0.722 and 95% CI 0.398 - 0.886). All correlations were statistically significant (P< 0.001).

Agreement	ICC	95%CI	P Value
Stride Time			
Inter Observer	0.97	0.937, 0.988	< 0.001
Intra Observer	0.992	0.98, 0.997	< 0.001
Stance Time			
Inter Observer	0.92	0.842, 0.965	< 0.001
Intra Observer	0.988	0.969, 0.995	< 0.001
Swing Time			
Inter Observer	0.509	0.237, 0.746	< 0.069
Intra Observer	0.722	0.398, 0.886	< 0.001
Double Stance Time			
Inter Observer	0.762	0.477, 0.927	< 0.05
Intra Observer	0.933	0.736, 0.984	< 0.001

Table 2a: *Inter- and intra-rater reliability. a: time related indices.*

Agreement	ICC	95%CI	P Value
Stride Length			
Inter Observer	0.996	0.992, 0.998	< 0.001
Intra Observer	0.995	0.986, 0.998	< 0.001
Step Length			
Inter Observer	0.996	0.991, 0.998	< 0.001
Intra Observer	0.998	0.994, 0.999	< 0.001

Table 2b: *Length related indices.*

CI = Confidence Interval.

Discussion

This study introduces a simple custom-built synchronized gait analysis system using three smartphones positioned around an open space walkway. The similarity of results regarding gait analysis obtained with this system when compared with a commercially available system demonstrates the validity of this custom-built system. Temporal parameters (stride time, stance time, swing time, and double stance time) and length parameters (step length, and stride length) were comparable between the two systems.

The reliability of temporal indices, with the exception of swing time, was all rated as good to excellent (correlation > 0.75). Measurements of length parameters (stride and step) were also in excellent agreement. These findings demonstrate that our custom-built system is satisfactory in evaluating kinematic variables required for gait analysis.

An alternative way to construct 3D coordinates is by using a specialized single video camera. Images captured with the single-color red-green-blue (RGB) camera combined with a depth infrared sensor (RGB-D) may be used for spatiotemporal analysis of gait [10]. Nevertheless, full validation of lower limb kinematics requires further examination, especially for perspective distance.

With technical advancement and new discoveries, our custom-built system may enhance the range of exploring activities that may involve faster movement. We have described that the calibrated space of 140 cm in length, 33 cm in width, and 80 cm in height is appropriate for ordinary gait analysis. As the calibrated space can also be enlarged in proportion to the size of the 'utility rack', another locomotive activity like jogging may be evaluated [23]. Regarding time resolution of video capture, the current slow video recording of 120 fps is sufficient for gait analysis, with newer models of smartphones capable of capturing even higher quality videos at 240 fps. This improvement also boosts searching range. In our limited experience, 50 fps cannot fulfill the required spectrum for a precise examination.

Our current system has several strengths. First, smartphones are powerful microcomputers with video cameras capable of capturing high quality videos much better than in the early 2000s [14]. As smartphone technology progresses, our simple system can also advance accordingly. Manufactured gait analysis systems and products could not be easily obtained nor frequently modified according to the user's request. Second, setting up our system is easy, approximately 15 minutes and operation is simple. In addition, our system is handy and can be transferred and set up almost anywhere and all necessary items could be purchased at shops with minimal expenditure. Even orthopedic surgeons in developing countries could use this system for gait analysis. Third, gait analysis from the different planes can be constructed from other selection of smartphones out of the three set. For example, combination of images from the frontal and 45 degrees oblique planes can resolve for coronal movement. Gait analysis from the rear can be also accessible from combination of the rear (coronal) and oblique planes. Fourth, present system can extend utility to measure joint angle parameter, by estimating from 3D coordinate values at three points, calculated mathematically from the 'inner product' and 'vector operation'.

This study possesses several limitations. First and most important is the small sample size consisting of only healthy individuals. Currently, a larger study involving postoperative patients with proximal femoral fractures is proceeding. Second, marking several spots (e.g. tip of great toes) on the computer screen to calculate for step and stride length may be subjective. Third, a small magnitude of skin movement may affect the sensitivity of this measurement system [24]. This limitation is difficult to overcome unless adhesive material is directly secured to the target bone [12,25]. Fourth, it takes approximately one hour on a computer to sort out and complete the whole analyzing process of the recorded data: transforming videos into stacks of static images on personal computers, selecting and digitizing images under ImageJ, and calculating measured values on Excel. This has been simplified by creating a mathematical formula, and we are currently working on a new application that can complete the whole procedure of data collection and analysis exclusively on smartphones [1,26]. In contrast, the commercially available system produces data automatically [24].

In the future, postoperative functional evaluation scores would place much importance on the patient's ambulatory status. Nevertheless, the recent majority of postoperative gait performance of patients are merely categorized into walking without aid, walking using a cane, or wheel chair users in many postoperative scoring in Orthopedic patients [27]. The availability of a ubiquitous and inexpensive device or system for gait evaluation, with an established validation, may allow for a more detailed examination that can quantify postoperative gait.

Conclusion

The proposed custom-built gait analyzing system consisting of three smartphones recording synchronized videos from divergent planes is a useful alternative gait analyzing system, when the commercially available system is not available. This system is very simple and inexpensive, and can be easily assembled in most local hospitals, even in developing countries.

Statements

This study was not funded and does not have any other conflict of interest.

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