Development and validation of a low-cost, portable and wireless gait assessment tool

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Abstract

Background: Performing gait analysis in a clinical setting can often be challenging due to time, cost and the availability of sophisticated three dimensional (3D) gait analysis systems. This study has developed and tested a portable wireless gait assessment tool (wi-GAT) to address these challenges.

Aim: To investigate the concurrent validity of the wi-GAT in measuring spatio-temporal gait parameters such as stride length, stride duration, cadence, double support time (DST), stance and swing time compared to a 3D Vicon motion analysis system.

Methods: Ten healthy volunteers participated in the study (age range 23-30 years). Spatio-temporal gait parameters were recorded simultaneously by the Vicon and the wi-GAT systems as each subject walked at their self-selected speed.

Results: The stride length and duration, cadence, stance duration and walking speed recorded using the wi-GAT showed strong agreement with those same parameters recorded by the Vicon (ICC of 0.94 to 0.996). A difference between the systems in registering "toe off" resulted in less agreement (ICC of 0.299 to 0.847) in gait parameters such as % stance and % swing and DST.

Discussion and Conclusion: The study demonstrated good concurrent validity for the wi-GAT system. The wi-GAT has the potential to be a useful assessment tool for clinicians.

1. Introduction

Gait analysis is a commonly used assessment tool that helps to quantify human locomotion. It has been widely used as a research and/or a clinical tool to quantify movement in various neurological conditions such as stroke [1, 2], cerebral palsy [3, 4], spinal cord injury [5], and also among the elderly population to assess the risk of falls [6]. Three dimensional (3D) gait analysis has evolved over the years as a tool that provides the most accurate measure of human movement. However access to this sophisticated system is often limited to movement laboratories within an academic institution or large hospitals with embedded research facilities [7]. In addition to limited access, the costs associated with gait assessments also make it difficult for clinicians to perform them routinely to monitor their patient's progress. It has been estimated that a gait study can cost anything up to $2000 and the cost to set up a movement laboratory can be on average about $300,000 [8].

In a recent review that reported on gait deficits in patients with traumatic brain injury, it was found that out of 15 studies that had used 3D gait analysis as an outcome measure only 2 of the studies reported on the kinematics and kinetics of gait [9]. The majority of the studies that were reviewed reported the temporal-spatial gait parameters, such as walking speed, cadence, stride duration, stride length and step length. A 3D gait analysis is often difficult to perform in a clinical setting, due to the reasons stated previously, however recording spatio-temporal gait parameters is less time consuming and feasible. The advantage of a 3D gait analysis is that provides extensive data that includes kinematics and kinetics, which often gait assessment tools that record spatio-temporal parameters alone, do not provide. There are commercially available gait assessment tools that can record spatio-temporal gait parameters such as instrumented mats with pressure sensors [10] and body worn sensors that incorporate accelerometers [11]. The limitations of these systems include difficulties in set-up within a clinical environment, where space is often limited, and although they may not be as expensive as the 3D gait analysis system, they are still costly for individual departments or independent rehabilitation clinics to utilize in providing a cost effective clinical assessment.

Therefore there is a need for a low-cost, low-tech alternative that provides accurate measures that can be easily used by rehabilitation professionals without specialist motion capture/analysis training and most importantly within a clinical environment. We have developed a system that meets these goals. The initial wired prototype of this portable low–cost gait assessment system was piloted among incomplete spinal cord injured patients as part of a clinical study that monitored recovery in walking among these patients [12]. We have now successfully developed a wireless version of this portable gait assessment system. Therefore the aim of this study was to establish the concurrent validity of spatio-temporal gait parameters recorded by this novel system among adult able bodied subjects.

2. Materials and Methods

The wi-GAT was recently upgraded as a standalone data acquisition device which required adaptations to its circuitry and data acquisition software, this justifies the need for a validation study. The spatio-temporal gait parameters which were validated include stride length, stride duration, cadence, stance duration, swing duration, stance%, swing%, double support duration and walking speed. These parameters were calculated using the definitions provided in Table 1. The Vicon (Vicon MX, Oxford Metrics, Oxford, UK) is a three dimensional motion analysis system which is commonly used for recording spatial and temporal gait parameters with high accuracy [13]. It was thus deemed an appropriate standard on which to validate the gait parameters recorded using the wi-GAT.

2.1 Materials

A custom designed printed circuit board (PCB) (Beta LAYOUT, Ireland) was used in the development of the wi-GAT. It incorporates a Bluetooth module (BlueGiga model: WT11, Espoo, Finland) and microcontroller chip (Microchip model: pic18f4520, Chandler, AZ, USA) powered by a 9V battery. The PCB is housed in a plastic enclosure with dimensions of 12x10x4.5cm and the total weight (including battery) is 225g. The small size and weight enables the device to be attached to a belt on the subject's waist during data collection. The device amplifies and transmits data from two instrumented insoles each comprising of four 13 mm diameter force sensing resistors (FSRs) (Interlink Electronics, Camarillo, CA, USA) which are used to capture temporal information during gait. These are positioned under the heel, 1st metatarsal head, 5th metatarsal head and the big toe as described by Granat et al. [14]. Insoles were custom-made for each subject using FootDoc foot impression sheets (Visual Footcare Technologies, LLC, NY, USA) to position the FSRs as accurately as possible under the location of each anatomical landmark previously described. Standard shoe insoles were trimmed to the correct size and FSRs were attached under a clear plastic film in the correct positions for collecting the foot contact data (Figure 1). The process to fabricate the insoles for various shoe sizes takes approximately 15 minutes. The insoles are connected via ribbon cable to the waist worn device (Figure 1). The wi-GAT uses a Bluetooth connection to a PC for data collection by an interface program implemented in LabVIEW (National Instruments Inc., Texas, USA). The signals were sampled at 30Hz and logged directly to a spreadsheet file.

The spatio-temporal gait parameters were also recorded simultaneously using a twelve camera Vicon MX system operating at 100Hz. The Vicon Plug-in-Gait lower limb marker set and model was used. Plug-in-Gait uses methodology which has been described by Davis et al. [15] and Kadaba et al. [16] and requires sixteen 15mm reflective markers to be attached to anatomical landmarks of the lower extremity.

2.2 Experimental Setup

The spatio-temporal gait parameters were recorded over a 10m walkway located within a gait lab at the Department of Biomedical Engineering, University of Strathclyde. The capture volume of the Vicon system was set to approximately 6x6x2m and was calibrated to the distance of the walkway using standardized protocols recommended by the manufacturer (Vicon MX, Oxford Metrics, Oxford, UK) at the beginning of each testing session.

2.3 Subjects

Ten healthy subjects with no known gait abnormalities volunteered to participate in the study. These included four males and six females with a mean age of 26.5 years (range 23 - 30 years). The average height of the subjects was 1.72m (1.6 - 1.87m range) with an average weight of 73kg (54 - 86kg range). Ethical approval for the study was provided by the Biomedical Engineering ethics committee at the University of Strathclyde and the volunteers were fully informed of the procedure and provided written consent.

2.4 Experimental Protocol

Subjects were required to wear flat-soled training shoes and shorts. Anthropometric data was recorded for each subject on arrival and reflective markers were then attached to their lower extremities. The instrumented insoles were placed in the subject’s shoes and the wi-GAT box was positioned on a belt around their waist. Each subject was given the opportunity to perform practice walks to allow familiarization with the equipment and the experimental procedure. During data capture each subject was instructed to walk at a self-selected comfortable speed [11]. The first 2m of the 10m walkway were used by the subject to accelerate to their self selected speed and the last 2m to decelerate to a stop at the end of the walkway [12], [13]. The middle 6m of the walkway was used for data capture. Subjects performed a total of ten trials each.

2.5 Extraction of Gait parameters

2.5.1 Vicon

Gait parameters were extracted from both the wi-GAT and the Vicon system for comparison. Vicon Nexus 1.7.1 software (Oxford Metrics, UK) was used to analyze the data recorded from the Vicon system. Although force plates were present at the center of the 10m walkway, they were not used for detecting the heel strike and toe off events of the stride cycle because the size and position of the force plates limited data capture to a distance of 1.2m or approximately a single stride cycle, compared to data recorded over 6m and multiple strides by the wi-GAT. Instead, the Vicon Nexus software was used to manually identify the heel strike and foot-off time points during each trial using the position of the xyz co-ordinates of the heel and toe marker as a point of reference. The 3D coordinates and time frame that corresponded to each event were then exported as an ASCII file. Although the Vicon Nexus software can compute gait parameters from gait event information using the "Generate gait cycle parameters" pipeline process, these values are only calculated from the first identified stride cycle and not averaged over every recorded stride. As the wi-GAT averages over a series of strides, to preserve as many similar calculation methods as possible between the two systems, the Vicon trajectory and gait event timing data was used to manually calculate the gait parameters using the same gait parameter definitions used by the wi-GAT. These definitions along with the algorithms used to determine the parameters from the Vicon data are outlined in Table 1. In this study the wi-GAT measured a mean of 2.54 strides (std. dev. of 0.58) and the Vicon a mean of 2.43 strides (std. dev. of 0.54) across subjects.

2.5.2 wi-GAT

In order to extract the gait parameters from the wi-GAT, software implemented in LabVIEW was used (refer to screenshot Figure 2). This software up samples the recorded data file from 30Hz to 100Hz to match the sampling frequency of the Vicon system. The gait parameters: stride length, stride duration, cadence, stance duration, swing duration, stance%, swing%, double support duration and walking speed are calculated by averaging the FSR temporal data from the entire trial. The values were then saved to an excel file for subsequent analysis.

2.6 Statistical Analysis

Statistical analyses of all the gait parameter data was performed using SPSS (version 20.0) software (IBM Corp., Armonk, N.Y). A preliminary descriptive analysis and the Shapiro Wilk test were used to ascertain that the data was distributed normally. In order to compare the gait parameters generated by both devices, the mean values were taken over the ten trials for each subject. Intra-class correlation coefficients (ICCs) of the type (2, k) with absolute agreement [17], and repeatability coefficients were used to evaluate the level of agreement between the wi-GAT and Vicon systems for averaged stride data, as performed and recommended by previous investigations [11]. The repeatability coefficient was calculated according to Bland and Altman as 1.96 times the standard deviation of the differences between the wi-GAT and Vicon measurements [18]. The difference between the two measurement systems is expected to be less than this coefficient with a probability of 95%. The repeatability coefficient was also calculated as a percentage of the mean value of the two measurement systems.

3. Results

Comparative data for the Vicon and wi-GAT systems are presented in Table 2. The mean value and standard deviation of each parameter from the ten subjects has been included to demonstrate the overall difference in measurement between the two systems. The majority of the ICCs (Table 2) demonstrate an excellent level of absolute agreement between the wi-GAT and Vicon systems. These range from 0.94 to 0.996. The ICCs which showed less agreement ranged from 0.299 to 0.847, these were observed in four of the parameters: swing duration, stance%, swing% and double support duration. It should be noted that the actual stance (0.94, 0.94) and swing (0.847, 0.782) duration had moderate to good agreement but due to the short duration of each stride, when normalized, the stance% and swing% showed less agreement. However, these differences were consistent across all the subjects and the repeatability coefficients (Table 2) were small in magnitude which may indicate that a close agreement still exists between the wi-GAT and Vicon. Small repeatability coefficients were observed for all of the gait parameters. For example, the absolute coefficient of 0.051m for left stride length in Table 2 indicates that the largest difference which can be expected between the two systems of data capture would be 5.1cm in 95% of the measurements.

Bland and Altman plots were produced for stride length, stride duration, cadence and walking speed for the left and right legs combined, Figure 3. This is to verify that the assumptions of the limits of agreement are correct [18, 19].

The mean value of the true error was calculated as the mean difference between the ten averaged subject walks to identify how much the parameter values differ between the two systems (as reported by [11]), Table 2. The mean percentage error was then calculated between the wi-GAT and the Vicon mean values. The mean percentage error was defined as the difference in the measurement between the two systems divided by the Vicon measurement and recorded as a percentage.

The parameters with the largest discrepancies are the parameters which use toe-off timing in their calculations (see Table 1). The largest difference in measurement was a 16% error in double support duration, which equates to a 0.024s or 24ms time difference.

4. Discussion

The validation results show good concurrent validity for most of the spatio-temporal gait parameters that were recorded using the wi-GAT. The two main advantages of the wi-GAT are its low-cost and ease of use in a clinical environment. There has been a lot of interest over the last decade on the development of low-cost gait assessment tools that can measure spatio-temporal gait parameters. The low-cost devices that have been developed so far include the use of two electric switches placed under the feet [20], ultrasonic sensors [21], photoelectric cells [22] and body worn gyroscopes [23]. Although most of these systems have used the term 'low-cost' in their description, the actual costs of these devices are not easy to estimate. The wi-GAT system uses low cost components and a standard communication protocol. This provides the basis of what could be a low cost commercial product capable of operating in conjunction with any Bluetooth enabled device with the ability to run compact software applications.

The second most important advantage of the portable wireless device is its ease of use in a clinical environment. Although the wi-GAT is yet to be used in a clinical setting, the wired version of this device was successfully used to evaluate gait in a study on gait recovery in incomplete spinal cord injured subjects [12] and in an investigation of the combined effects of functional electrical stimulation and Botulinum toxin on walking in children with cerebral palsy [3]. The total duration to setup the portable wireless device and record the spatio-temporal gait parameters during a single trial is under 10 minutes, provided that insoles of various sizes are already instrumented and available. The analysis of the data using the graphical user interface (Figure 2) is simple with only two buttons for activation, meaning analysis can be completed in less than 2 minutes. This we believe would encourage clinical use as the test is simple to perform, provides rapid reporting and can be completed within a single consultation.

The concurrent validity of the wi-GAT is comparable to other devices that have been developed to record spatio-temporal gait parameters such as body worn gyroscopes [11], and photoelectric cell walkways [22]. The spatio-temporal gait parameters: walking speed, stride length, stride duration, stance duration and cadence showed excellent agreement with the values estimated by the Vicon 3D motion analysis system (ICC values between 0.99 and 0.94) (Table 2). The % errors for the above mentioned spatio-temporal parameters were also low and ranged between 0.25% and 2.2%. Given the low-cost and low-technology attributes of the portable wireless device, these are excellent agreements between a sophisticated 3D motion analysis system and the wi-GAT.

The other spatio-temporal parameters calculated, swing duration and double support time, showed lesser levels of agreement between the wi-GAT and the Vicon 3D motion analysis system (ICC values between 0.84 and 0.49) (Table 2). The reasons for this lesser agreement are thought to be due to anatomical reasons combined with the differences in the methods of estimation used by the wi-GAT and the Vicon 3D motion analysis systems. The gait analysis device uses an FSR positioned under the big toe to estimate toe-off as the time instance when this footswitch switches off. Whereas toe-off is identified by Vicon by manually entering a gait event in the software when the toe marker located over the 2nd metatarsal head has just left the ground. Due to the discrepancy in the timing of these toe-off events due to the anatomical difference in the placement of the FSR and marker, the stance% values for the wi-GAT are slightly larger and thus the swing% values are slightly smaller than the values estimated by the Vicon 3D motion analysis systems. These differences were typically in the range of a few milliseconds. However when they were normalized in respect to the duration of a single gait cycle, the percentage errors were in the region of 3-6.5% (Table 2). Similar differences in gait cycle durations have also been reported in a system that uses optoelectric cells to record spatio-temporal gait parameters [22]. Because these errors are consistent, the wi-GAT is a valid tool to assess the spatio-temporal gait parameters.

There are some limitations in the present study. The wi-GAT has been validated only among young healthy adults (23-30 years). A study is already underway to investigate the spatio-temporal gait parameters in a geriatric population. Also in the current study subjects were asked to walk using a self-selected speed. A future study is being planned to evaluate the validity of the recorded spatio-temporal gait parameters using the wi-GAT during slow, regular and fast walking speeds and also establish the test-retest repeatability, which the current study has not investigated. The wi-GAT is yet to be used in a clinical population. In order to address this, a study is being planned to investigate the recovery of gait among incomplete spinal cord injured subjects using the wi-GAT in a clinical setup.

There are also other gait parameters that the wi-GAT has a capability to record such as the mode of initial contact, heel contact time, inversion/eversion of the foot and the asymmetry index. These are often important clinical indicators that provide the clinician with a wealth of information. For example data on the mode of initial contact provides the clinician with an insight on the patient's motor control of the foot during walking. Any muscle tightness or spasticity can also strongly influence the mode of initial contact. Therefore besides estimating the spatio-temporal gait parameters, the wi-GAT can also provide other clinically relevant data on the patient's gait.

5. Conclusion

The wi-GAT has shown good concurrent validity when compared with the Vicon 3D gait analysis system, as shown by the excellent ICC values and low measurement errors. The low-cost, low-technology and user friendly graphical interface makes it an ideal tool for clinicians to use as an assessment tool in their clinics. The time taken to setup and record the spatio-temporal gait parameters are also minimal. The wi-GAT also provides additional data on initial contact pattern, heel contact time and other clinically relevant data, as shown in previous studies that have used this device.

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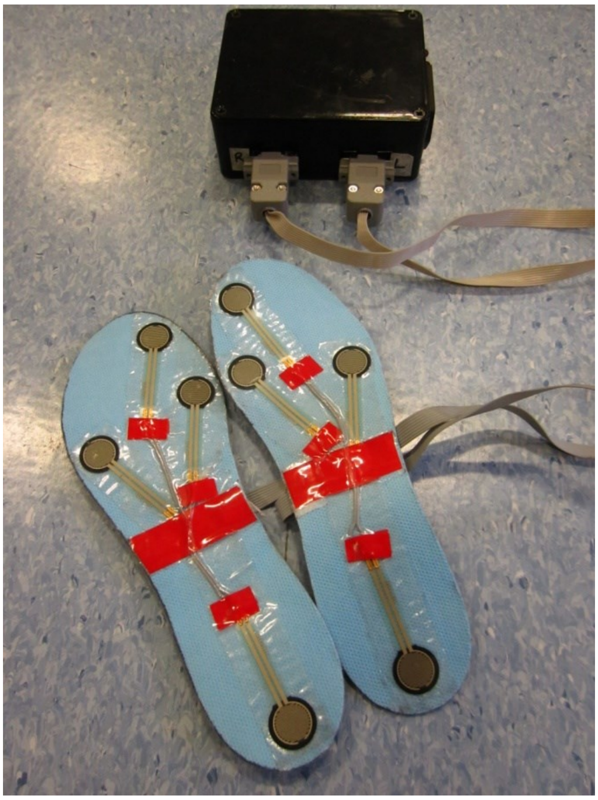

Figure 1: Wi-GAT device and FSR insoles.

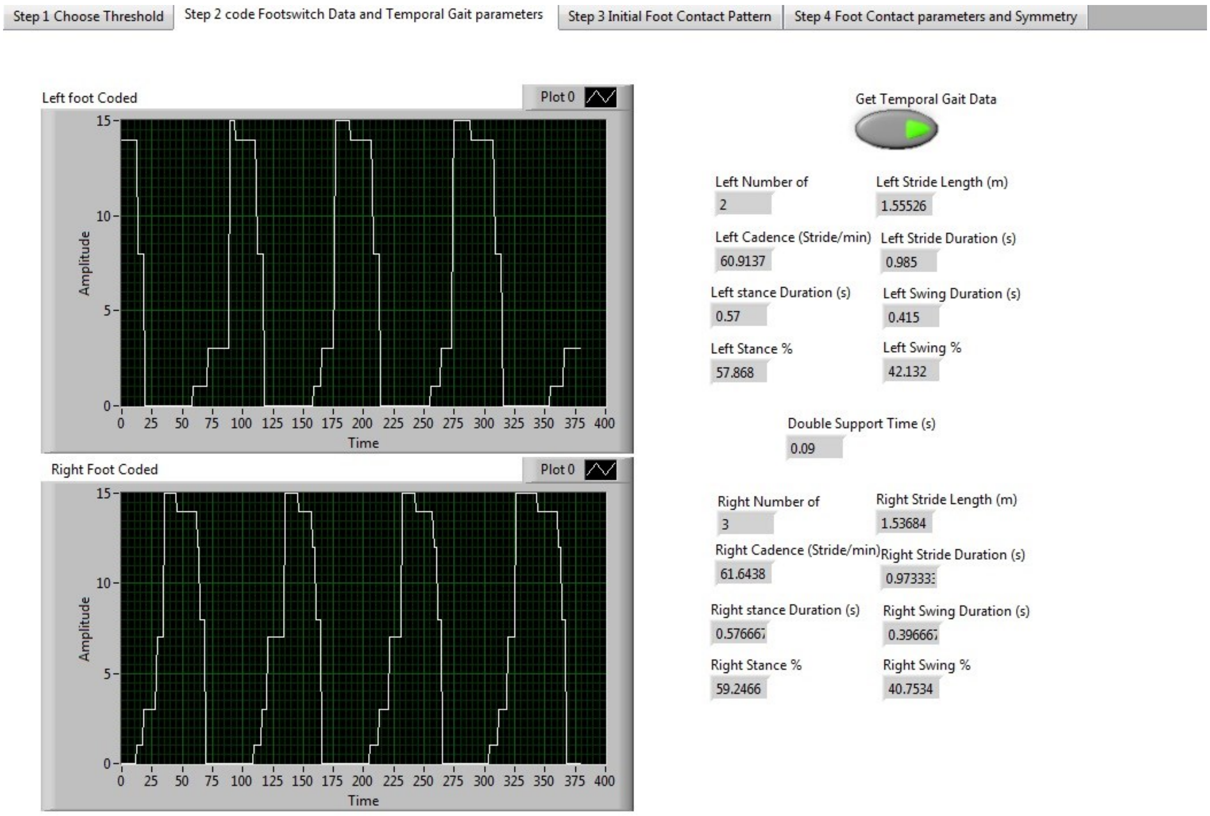

Figure 2: Screen shot of the wi-GAT analysis software. The software automatically calculates the spatio-temporal gait parameters when a gait recording is selected. The spatio-temporal values can then be saved to a spreadsheet for further analysis.

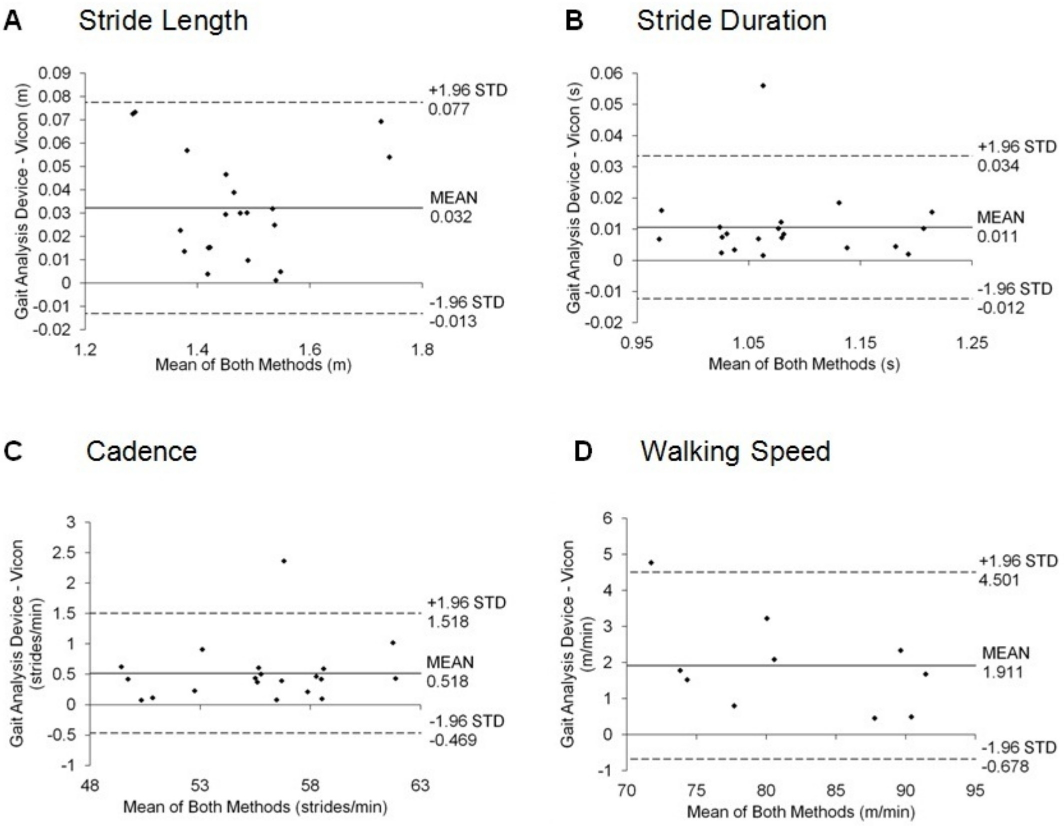

Figure 3: Bland and Altman plots of stride length, stride duration, cadence and walking speed for the left and right legs combined. The difference between the two systems (gait analysis device – Vicon) is plotted against the mean value of both devices for each subject. Limits of agreement are included as the mean value +/- 1.96 standard deviations (STD).

Table 1

The spatial and temporal gait parameter definitions used by the gait analysis device for the calculations are shown below. Foot strike was taken as the instance of a heel FSR switching over a given threshold and foot off as a time when no signal from the FSRs was measured for that particular foot. Definitions taken from [24].

Gait Parameters	Definition	Vicon Calculation
Stride Length (m)	Distance covered between two subsequent foot strikes of the same foot.	$L = \frac{1}{n}\sum_{i=1}^{n}(x_{heel_{i+1}} - x_{heel_i})$ Where x_{heel} is the x coordinate (direction of walking) of the heel marker at heel strike.
Stride Duration (s)	Time taken to complete a single stride.	$D = \frac{1}{n}\sum_{i=1}^{n}(t_{heel_{i+1}} - t_{heel_i})$ Where t_{heel} is the time of heel strike in seconds.
Cadence (strides/min)	The number of strides taken in 1 minute.	
Stance Duration (s)	Time taken from foot strike to the foot off of the same leg.	$St = \frac{1}{n}\sum_{i=1}^{n}(t_{toe_i} - t_{heel_i})$ Where t_{toe} is the time when the toe marker leaves the ground in seconds.
Swing Duration (s)	Time taken from foot off until the next foot strike of the same leg.	$Sw = \frac{1}{n}\sum_{i=1}^{n}(t_{heel_i} - t_{toe_i})$
Stance (%)	Percentage of the gait cycle when the foot is in contact with the ground (period between foot strike and ipsilateral foot off).	
Swing (%)	Percentage of the gait cycle when the foot is in the air (starting with foot off and ending with the second ipsilateral foot strike).	
Double Support Duration (s)	Time taken from foot strike to opposite foot off.	$Ds = \frac{1}{n}\sum_{i=1}^{n}(t_{toe(opp)_i} - t_{heel_i})$

Walking Speed (m/min)	Total distance travelled divided by the time taken to cover that distance.

Table 2

Mean (Std. Dev) values of each gait parameter averaged across all ten subjects for both the gait analysis and Vicon systems. Intra-class correlation coefficients (ICCs) and repeatability coefficients are also provided.

	Average (Std. Dev)		Difference Between Systems		Repeatability Coefficients		
Gait Parameters	Gait analysis system	Vicon	(Gait Analysis Device - Vicon)	% Error	Absolute	Mean (%)	ICC
Stride Length, L (m)	1.454 (0.121)	1.484 (0.121)	-0.030	-2.005	0.051	3.468	0.973
Stride Length, R (m)	1.458 (0.121)	1.485 (0.122)	-0.027	-1.805	0.042	2.823	0.975
Stride Duration, L (s)	1.083 (0.077)	1.081 (0.077)	0.003	0.262	0.011	1.049	0.996
Stride Duration, R (s)	1.086 (0.072)	1.080 (0.075)	0.007	0.626	0.030	2.773	0.981
Cadence, L (strides/min)	55.654 (3.816)	55.791 (3.889)	-0.137	-0.245	0.529	0.950	0.996
Cadence, R (strides/min)	55.530 (3.621)	55.837 (3.821)	-0.307	-0.550	1.268	2.277	0.985
Stance Duration, L (s)	0.666 (0.050)	0.687 (0.048)	-0.021	-3.016	0.024	3.567	0.940
Stance Duration, R (s)	0.671 (0.048)	0.693 (0.050)	-0.021	-3.103	0.024	3.454	0.940
Swing Duration, L (s)	0.417(0.031)	0.394(0.034)	0.023	5.803	0.027	6.649	0.847
Swing Duration, R (s)	0.415 (0.028)	0.388 (0.032)	0.027	7.046	0.026	6.472	0.782
Stance, L (%)	61.502 (1.118)	63.602 (1.155)	-2.100	-3.302	2.302	3.680	0.299
Stance, R (%)	61.779 (0.953)	64.130 (1.145)	-2.351	-3.666	1.555	2.470	0.343
Swing, L (%)	38.498 (1.118)	36.461 (1.264)	2.038	5.589	2.362	6.303	0.338
Swing, R (%)	38.221 (0.953)	35.920 (1.213)	2.301	6.405	1.756	4.737	0.344
Double Support (s)	0.125 (0.013)	0.150 (0.015)	-0.024	-16.241	0.017	12.069	0.494
Walking Speed (m/min)	80.830 (7.900)	82.645 (7.147)	-1.814	-2.196	2.590	3.168	0.977

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