Medical Engineering and Physics 111 (2023) 103925

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Accuracy of the fully integrated Insole3's estimates of spatiotemporal parameters during walking

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ARTICLE INFO

Keywords:
Gait analysis
Pressure insole
Spatiotemporal variables
Validation
Wearables

ABSTRACT

This study investigated the accuracy of the Insole3 wireless shoe device in estimating several clinically useful spatiotemporal parameters (STPs). Eleven subjects walked at slow (0.8–1.0 m/s) and moderate-paced (1.2–1.4 m/s) speeds. Data were simultaneously recorded using the Insole3 and an industry-standard, three-dimensional motion capture (MOCAP) system. An error analysis compared the resulting STP data from the two systems. The mean bias error (MBE) was generally lower for temporal variables, and somewhat higher, but acceptable, for spatial variables. The MBE for temporally-related cadence and cycle time were the lowest (less than ±0.45%), with 100% (110/110) of slow-paced walking trial values and 99.1% (109/110) of moderate-paced walking trial values within 5% of the MOCAP estimates. The MBE was highest for speed (3.23–4.91%) and stride length (3.68–4.63%), with between 52.7 and 69.1% of trial values falling within the 5% error range. Stance time and swing time ranged between -0.98 and 4.38% error for both walking conditions. The results of this study suggest that the Insole3 is a potential alternative to MOCAP for estimating several STPs, namely cadence, stance time, and cycle time, particularly for use outside of the laboratory setting.

1. Introduction

Gait analysis has a variety of uses in the clinical assessment of patients [1]. Clinical analysis of gait can provide us with information to guide diagnosis, treatment, and rehabilitation in many pathologies from neuromuscular to musculoskeletal disease [2,3]. One of the primary domains examined in gait are metrics related to how the body moves through space and time, or spatiotemporal parameters (STPs). STPs include spatial variables such as walking speed and stride length, as well as temporal variables including cadence and stance time [4]. These parameters have shown utility in various clinically relevant research questions, such as those investigating the incidence of disability while aging [5], predicting the incidence of falls [6], and even the risk of cognitive decline and dementia [7]. Thus, the accurate measurement of spatiotemporal variables is integral in both research and clinical domains.

Current methods for measuring spatiotemporal variables in a laboratory setting are numerous and include dual laser range sensors [8], walkway systems [9], and stopwatches. Previous studies have used three-dimensional motion capture systems as the industry standard for comparing other technologies [10,11]. These devices can provide accurate data using optoelectronic infrared motion capture systems to measure retroreflective marker positions over time, combined with force plates to enhance the detection of gait events [12]. Although accurate, MOCAP systems are expensive and require a dedicated laboratory space with trained personnel to operate them, factors that greatly limit their everyday or clinical utility [10]. In the past decade, there has been a push for more practical, clinically useful methods of measuring spatiotemporal parameters of gait with the emergence of wearable inertial measurement units (IMUs).

The Insole3 (Moticon ReGo AG, Munich, Germany) (Fig. 1) is one of several "smart-insoles" containing IMUs to allow gait assessments not only in a laboratory, but also in the home and community settings. There are a variety of different insoles on the market, but their general design includes an insole device that can be inserted into a shoe and contains one or more of the following: pressure sensor, accelerometer, gyroscope, or magnetometer [13]. These devices have the benefit of being able to collect data in both laboratory and field settings and can be easily

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https://doi.org/10.1016/j.medengphy.2022.103925
Received 8 May 2022; Received in revised form 23 September 2022; Accepted 15 November 2022
Available online 17 November 2022

applied in clinical assessment and treatment, sports performance analysis, and in the prevention of injury [11]. In addition, they allow for the unobtrusive monitoring of daily activity without wires or external devices. A systematic review of seventeen different insole models demonstrated that instrumented insoles are highly accurate at step counting [13]. Research into specific insoles such as the Digitsole SAS PODOsmart shows that it can accurately measure STPs including cadence, speed, and step duration with intraclass correlation coefficients (ICCs) >0.916; however other variables such as double support time (ICC=0.784), swing duration (ICCs=0.568–0.575), and swing time (ICCs 0.525–0.663) were less accurate [11]. A study of the OpenGo insole, the predecessor to the Insole3, demonstrated excellent ICCs (>0.90) for left/right stance time, gait cycle time, and cadence when compared to an instrumented treadmill. The study, however, did not investigate speed, an important variable to assess patients in the clinic [14] and community settings.

Wearable IMUs, which use integrated accelerometers, gyroscopes and magnetometers to estimate STPs, are traditionally fixed to the lower limb which increases set-up time and can alter a participants' gait. Furthermore, they are unable to provide valuable pressure and vertical force data. The Insole3 contains an integrated IMU measuring three linear accelerations and three angular velocities in space in addition to sixteen pressure sensors for force assessment. It processes a multitude of spatiotemporal variables including cadence, speed, gait cycle time, swing time, stance time, and stride length. Such integration of pressure sensors and an IMU into a single wireless device for assessing force and STPs together can be an extremely valuable asset in many clinical settings and for a multitude of clinical populations [15,16]. The Insole3 can wirelessly transfer data in real-time to a computer or phone (Fig. 1), or store data within the insole that can later be transferred via Bluetooth to a computer [17].

Given the immense utility of instrumental insoles that demonstrate accurate STP estimations, we aim to study the accuracy of STP estimations from the Insole3. A prior study has demonstrated evidence towards the insole's validity in measuring force parameters [18], but its use in measuring STPs has not yet been investigated. Therefore, the purpose of this study is to investigate the accuracy of spatiotemporal variables estimated by the Insole3 when compared to those outputed by MOCAP.

2. Methods

2.1. Subjects

This study was approved by the Rush Institutional Review Board (Rush ORA-12021506) and was part of a larger prospective, observational study to validate force as the primary variable [18] and evaluate STPs as secondary variables. Eleven subjects were indicated from an a priori power analysis to yield sufficient power (80%; α =0.05) using means and standard deviations for force [18]. Healthy subjects were recruited by word of mouth and provided informed consent for the study. All subjects self-reported as healthy, pain-free, able to walk/run two blocks without assistance, and having no history of surgery in the ankles, knees, or hips.

2.2. Instruments

2.2.1. Three-dimensional motion capture (MOCAP)

The motion capture system (MOCAP) included twelve optoelectronic infrared motion capture cameras (Qualisys AB, Gothenburg, Sweden), which recorded motion at 100 Hz, combined with two in-ground force plates (Bertec Corporation, Columbus, Ohio) to measure ground reaction forces during all walking trials (Fig. 2). The motion and force data together were used to calculate STPs. Wearing a standardized shirt and shorts, reflective markers were applied directly to subjects' skin as per a modified Helen Hayes protocol [19]. Additional markers were placed on the shoe surface overlying the second and fifth metatarsal heads, tip of the second toe, and posterolateral heel. Following standing trials, reference markers on the medial malleolus and medial knee were removed.

2.2.2. Insoles

The Insole3 device was used concomitantly with the 3D motion capture system during all walking trials. Data were collected at the highest possible rate of 100 Hz, stored on the insole's onboard SD memory card, and then transferred via Bluetooth to a computer containing the insole manufacturer's OpenGo software (Moticon ReGo AG, Munich, Germany).

Participants wore an appropriately-fitted insole contained within a standardized shoe (Adidas low-cut VRX, model DB3176) along with low-cut socks to accommodate the markers on the medial and lateral malleoli. Since large fluctuations in temperature and humidity can lead to measurement drift and cause frequent re-calibrations, the insoles were

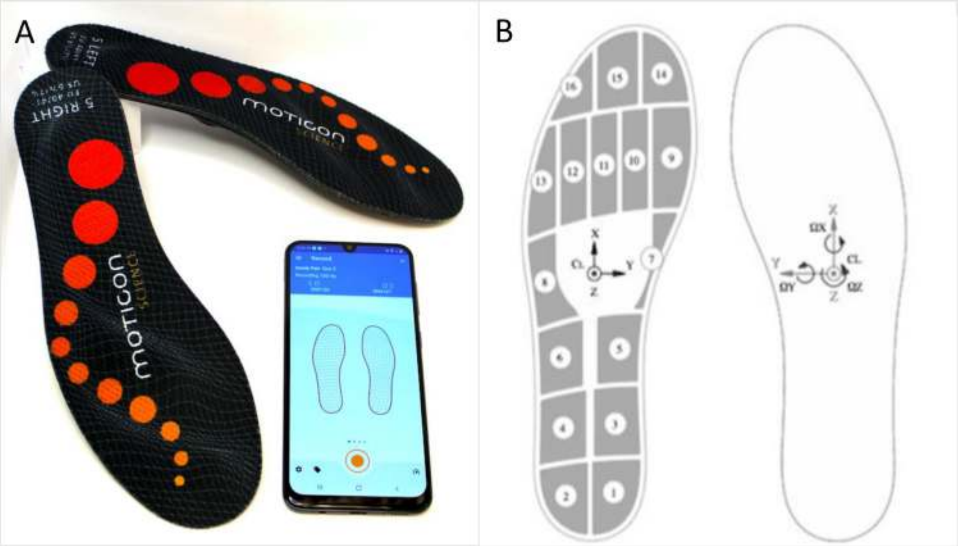

Fig. 1. A. The Insole3 and the Moticon OpenGo application on a smartphone. B. Insole3 pressure sensors layout with integrated IMU (Moticon ReGo AG).

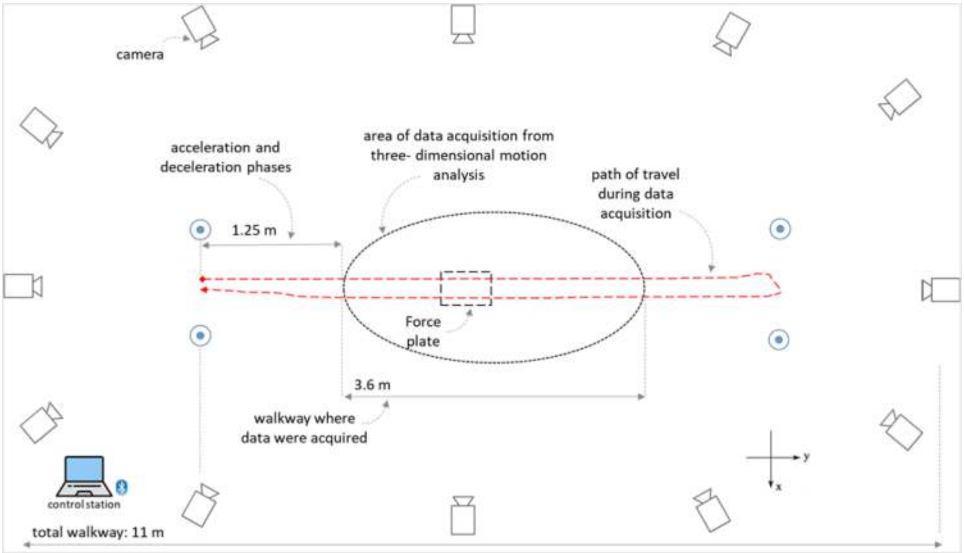

Fig. 2. The motion analysis laboratory layout and walking path.

worn in the shoe during marker placement, system calibration, and a brief walking warm-up, which allowed the devices to acclimate to the subject's body temperature [20].

Insoles were calibrated on the Insole3's OpenGo mobile application to the participants' bodyweight as measured by a standard balance scale, per the manufacturer's guidelines. The calibration included subjects walking very slowly for 40 s, standing still for 10 s, shifting their weight anteriorly-posteriorly for 10 s, and performing lateral weight shifts for a final 10 s. At the end of calibration, successful zeroing was confirmed by visualizing zero total force on either insole of a raised leg during unilateral stance.

Table 1
Definitions of spatiotemporal parameters (STPs).

Variable	Definition
Cadence	Number of strides per minute
Cycle time	Time from initial contact one foot to initial contact of the same foot, averaged over all steps
Speed	Speed of the subject
Stance time	Time from initial contact to toe off (of respective foot side), averaged over all steps
Stride length	Displacement of the same foot in the direction of walking
Swing time	Time from toe off to heel strike (of respective extremity) averaged over all steps

2.3. Gait conditions

To determine the insole's concurrent validity under two different walking speeds, participants performed ten waking trials each for slow and moderate-paced walking. Five of the ten trials were processed in MOCAP software by indexing the right leg, with the other five trials indexing the left leg. Therefore, a total of twenty walking trials were performed by each subject. The target speeds were 0.8–1.0 m/s for slow-paced walking and 1.2–1.4 m/s for moderate-paced walking. Participants acclimated to these speeds by first performing practice trials. After participants consistently performed practice trials within the reference speed range, the walking trials were recorded. During recorded walking trials, slow and moderate-paced speeds were initially verified using a stopwatch to record the time it took the study subject to walk across the 6.1 m (20 ft) of 3D motion capture recording volume in the laboratory.

2.4. Data processing

Foot markers and force plate data were processed in Visual3D (C-Motion, Inc., Germantown, MD). Marker data was low-pass filtered in V3D at 6 Hz, and force plate data at 15 Hz using a zero-lag fourth-order Butterworth filter. This filter was used to smooth biomechanical data and followed values of earlier studies, in which it showed benefit [21]. Visual3D relies on a function called "Automatic Gait Events," which uses marker and force plate data to determine heel strike, toe off, and second heel strike events [22]. The timing and position of heel strike and toe off events are used to calculate spatiotemporal variables. Variables of interest include speed, cadence, gait cycle time, stance time, stride length, and swing time. Definitions of these variables are listed in Table 1.

Insole data were analyzed utilizing the Insole3's OpenGo software and time-matched between Visual3D and Insole3 so the same gait cycles could be compared between the two systems. A flash of light from the phone linked to the insole device marked the end of the recording and was in clear view of the motion capture system camera. This flash served to synchronize timestamps between the force plates and the insoles. While the Insole3 manufacturer recommends a minimum of five steps, or two and a half strides, as an acceptable window to process STPs, we applied a gating window of eight steps, or four strides, to align with the same number of steps captured and analyzed by the MOCAP system. We also processed the Insole3 data with the aforementioned manufacturer recommendation of five steps to determine if there was a noticeable change in accuracy compared with MOCAP.

2.5. Statistical analysis

The STPs estimated by the Insole3 were compared to those estimated by MOCAP using error analysis and Bland-Altman plots. Error analyses were performed by calculating the percent error between the insoles and motion capture data using each individual trial for a direct comparison of speed, cadence, cycle time, stride length, swing time, and stance time for both slow and moderate pace. For the error analysis, the percent error for individual trials were calculated and grouped into the following error ranges: >10% error, >5 and ≤10% error, >2 and ≤5% error, ≥0 and ≤2% error, ≥-2 and <0% error, ≥-5 and <-2% error, ≥-10 and <-5% error, and <-10% error. To further understand the performance of the Insole3 and its absolute deviation from MOCAP values, root mean square error (RMSE) and mean bias error (MBE) were calculated for each STP over both walking speeds. Modified Bland-Altman plots including limits of agreement (LOA) were created displaying differences of cadence, cycle time, speed, stride length, swing time, and stance time between the insoles and motion capture data using each individual trial for a direct comparison. The LOA were calculated as two standard deviations of differences. Biases were calculated by taking the mean paired difference between the measurements from the insoles and motion capture.

3. Results

Demographics of the eleven healthy subjects who participated in this study are listed in Table 2. Results for the eleven subjects are shown in Table 3, including descriptive statistics, RMSE, and MBE of the Insole3 values compared with the MOCAP values. The lowest mean bias is seen for temporal variables (cadence and cycle time), whereas the highest mean bias is seen for spatial variables (speed and stride length). Cadence has the highest RMSE, whereas the lowest RMSE is seen for cycle time, stance time, and swing time for both walking speeds. Table 4 organizes all the acquired gait trials by the percent error of the Insole3's STP estimates.

The Insole3's estimates of temporally-related parameters had lower errors than spatially-related parameters when compared with MOCAP. The MBE for cadence and cycle time were less than 0.45%, with 100% of slow-paced walking trial values and 99.1% of moderate-paced walking trial values within 5% of the MOCAP estimates. Stance time was more accurate during moderate-paced walking with a MBE of only -0.98%, with 98.1% of trial values falling within 5% of the MOCAP estimates; however, during slow walking the MBE was higher but respectable at -3.16%, driven by 83.6% of walking trial values falling with 5% of the MOCAP estimates. Conversely, the accuracy of the Insole3's estimation for swing time was lower during slow-paced walking, with a MBE of 4.38% that went down to 2.16% at moderate-paced speeds. This was reflected with 76.3% of slow-paced walking trial values and 58.1% of moderate-paced walking trial values falling within 5% error of MOCAP. The highest MBEs, between 3.23 and 4.91%, were observed for speed and stride length, with between 52.7 and 69.1% of trial values falling within the 5% error range.

Modified Bland-Altman plots for agreement between the Insole3 and MOCAP are demonstrated in Fig. 3. Cadence demonstrates a bias of -0.16 steps/min for moderate-paced walking and 0.203 steps/min for slow-paced walking, suggesting less than a step per minute discrepancy between the Insole3 and MOCAP. The plots also demonstrate that during moderate-paced walking, the Insole3 estimates slightly shorter stance times (<0.02 s) and slightly longer swing times (< 0.02 s) as compared to those measured by MOCAP. These differences are magnified during slow walking, but with all subject estimates at a difference of less than 0.05 s, the errors are still rather low. Biases for cycle time are 0.004 s and -0.005 s for moderate and slow-paced walking, respectively, with narrow limits of agreement (LOA) (<0.03 s). Biases for speed are 0.042 m/s for moderated-paced walking and 0.046 m/s for slow-paced walking, suggesting a slight overestimation of speed with the Insole3. However, LOA are significantly wider with moderate-paced as compared to slow-paced walking. A similar pattern is seen for stride length with biases of 0.053 m for moderate pace and 0.057 m for slow pace, suggesting a slight overestimation of stride length with the Insole3. Once again, the LOA are around twice as wide with moderate-paced as compared to slow-paced walking. Of the few mean values that lie outside of the LOA, almost all of them were from subject 08. Mean Insole3 generated values from subject 02 also showed significant variation compared to MOCAP, although not as significant a deviation as subject 08. These two subjects are represented by red data points on the Bland-Altman plots in Fig. 3.

Table 2
Participant characteristics ($n = 11$).

Demographic	Mean ± SD
Female/Male (% Female)	3/11 (27%)
Height (inches)	68.5 ± 3.5
Age (years)	33.1 ± 3.5
Weight (kilograms)	74.2 ± 14.6
BMI (kilograms/meter^2)	24.6 ± 4.4
Insole Size, European (median, range)	42/43 (36/37 – 44/45)

Table 3
Descriptive statistics, root mean square error, and mean biases for variables of interest.

Condition	Variable	MOCAP (Mean ± SD)	Insole3 (Mean ± SD)	Root Mean Square Error	Mean Bias [%]
Slow-paced Walk	Cadence (steps/min)	45.77 ± 2.25	45.97 ± 2.24	0.667	0.44
	Cycle time (s)	1.31 ± 0.06	1.31 ± 0.07	0.018	-0.35
	Speed (m/s)	0.94 ± 0.04	0.99 ± 0.08	0.083	4.91
	Stance time (s)	0.86 ± 0.05	0.83 ± 0.05	0.033	-3.16
	Stride length (m)	1.24 ± 0.06	1.29 ± 0.13	0.108	4.63
	Swing time (s)	0.46 ± 0.03	0.48 ± 0.03	0.029	4.38
Moderate-paced Walk	Cadence (steps/min)	54.89 ± 1.92	54.73 ± 1.89	0.813	-0.29
	Cycle time (s)	1.09 ± 0.04	1.10 ± 0.04	0.016	0.35
	Speed (m/s)	1.31 ± 0.04	1.35 ± 0.18	0.184	3.23
	Stance time (s)	0.69 ± 0.03	0.68 ± 0.03	0.016	-0.98
	Stride length (m)	1.43 ± 0.05	1.48 ± 0.22	0.205	3.68
	Swing time (s)	0.41 ± 0.02	0.41 ± 0.02	0.017	2.16

4. Discussion

This study investigated the accuracy of the Insole3 to estimate STPs during walking, an activity that is often clinically assessed and is the most commonly reported form of exercise [23]. The highest accuracy was found for estimates of temporal parameters including gait cycle time, cadence, and stance time, while the lowest accuracy was found for estimates of spatial parameters and their derivatives including stride length and walking speed. Spatial variables such as stride length may be error prone since calculating distance from IMUs involves the double integration of acceleration signals, which will inflate the measurement error.

The Bland-Altman plots indicate that the Insole3 tends to slightly overestimate swing time and, to a lesser extent, underestimate stance time. If our assumption of the utilization of pressure data is true, this phenomenon could be explained by the toe-off events not being detected as well by this device due to the sensor coverage of the insole. The Bland-Altman plots, which show the bias for each STP when the trials for each subject are averaged, also suggest a lower bias for speed and stride length than is initially indicated by the percent error for individual trials. This is important to point out since stride length is an important factor when considering joint loading [24], and gait speed is monitored across clinical populations to assess overall functional mobility [25], fall risk [26] and post-operative recovery [27]. With percent biases at <5% for both speed and stride length when trials are averaged, the Insole3's estimation accuracy of these variables may be acceptable for most clinical applications.

A similar agreement pattern as seen between the Insole3 and MOCAP in this study is found in the literature for other insole devices. Investigation of the PODOsmart insole demonstrated the highest agreement in cadence, speed, and step duration [11]. An analysis of the OpenGo insole

Table 4
Percent error brackets and number of trials that fell into these brackets for various spatiotemporal parameters. (Total trial number per speed = 110). Shading indicates trials outside the 5% error margin.

	Cadence		Cycle time		Speed		Stance time		Stride length		Swing time	
Percent error	Slow pace	Mod pace	Slow pace	Mod pace	Slow pace	Mod pace	Slow pace	Mod pace	Slow pace	Mod pace	Slow pace	Mod pace
>10	0	0	0	0	23	18	0	1	21	16	14	3
>5 and ≤10	0	0	0	1	24	8	0	1	25	9	29	18
>2 and ≤5	13	5	4	7	19	12	1	4	13	13	36	37
≥ 0 and ≤2	59	39	34	56	10	9	6	24	14	15	16	27
≥-2 and <0	34	60	62	42	16	19	23	45	19	17	10	14
≥-5 and <-2	4	5	10	4	16	32	62	35	12	31	2	6
≥-10 and <-5	0	1	0	0	2	10	18	0	6	9	3	5
<-10	0	0	0	0	0	2	0	0	0	0	0	0

also demonstrated the highest agreement for left/right stance time, gait cycle time, and cadence [14]. With regards to spatial variables, the PODOsmart insole demonstrated high agreement for speed and stride length [11]. Analysis of IMUs such as the LEGSys+ and APDM also produced accurate data with regards to spatial variables [15,16]. Although the Insole3 has lower agreement for speed and stride length than other STPs, percent biases for these two variables are less than 5% when applying longer capture windows and averaging multiple trials. Conversely, the higher percent error values for speed and stride length observed in several trials suggest that caution should be taken when attempting to assess these STPs with single walking trials or when assessing a few steps within each trial.

The most sought-after gait events in the portable assessment of STPs are the temporal parameters of heel-strike and toe-off [28]. Similar to other insoles such as the OpenGo [29] (the Insole3's predecessor) and PODOsmart [11], the Insole3 excels at detecting these events, which is likely a large reason this insole accurately estimates temporal parameters such as cadence, swing time, stance time, and gait cycle time. The Insole3's highest accuracy is in estimating cadence, a variable that can be used to examine both ambulatory performance in laboratory conditions as well as behavior in the real world [30]. With a strong association between higher cadences and the intensity of exercise [31] as well as lower body mass indices and higher general activity levels [31], the Insole3 has great potential for community-based assessment of these important markers of health. With the Insole3 being effective in collecting peak cadences within a short capture window, it may be particularly useful in a clinical setting for quick assessments such as the Timed Up and Go test, a well-validated tool for evaluating functional mobility in older populations [32].

The Insole3 was less accurate in estimating speed and stride length, but most of the discrepancy was seen in two of the eleven subjects. Our data processing protocol analyzed eight steps within the insole's OpenGo processing software in order to best match to the same steps analyzed with MOCAP. The manufacturer's minimal requirement for exporting STPs, however, is only five steps. Increasing from five steps to eight steps for processing data resulted in a noticeable reduction in error for both subjects, which translated to some improvement in accuracy. For instance, the mean error in one subject's speed estimations decreased from 4.87% to 4.11% and mean error for stride length decreased from 5.06% to 4.04%. Thus, ensuring an adequate number of steps during trial acquisition and including a greater number of steps at the target speed within the insole analysis software may be beneficial when evaluating speed and stride length. Fortunately, the Insole3 is capable of continuously recording many minutes of walking, thereby addressing a huge limitation of MOCAP's small capture volume that yields a low number of gait cycles per trial. While many clinical environments have small areas to assess gait, the Insole3's OpenGo software allows for cutting out walking segments involving deceleration phases, turning phases, and accelerations, which enables the end-user to combine only those walking segments where full speed is maintained.

There are several limitations of our study to be considered. The initial power analysis was performed to study force, not STPs, which were considered secondary variables. However, in difference to the initial study where trial averages per subject were inputted into statistical models, here we conduct a trial-based, descriptive error analysis. Another limitation concerns the confines of laboratory space, including a small acquisition volume for MOCAP and a short walkway, measuring 6.1 m. While the Insole3 is designed for longer capture times, we were unable to use longer walkways and capture more steps for comparison. This eight-step comparison, however, was still higher than the insole manufacturer's five step minimum, and was still able to exclude phases of acceleration and deceleration from the window for analysis. Furthermore, the limited walkway length helped in reproducing a clinical scenario, such as a clinician's office, where patients may only be taking a few steps due to the confines of the exam space. Also, due to the limited availability of standardized shoe sizes, subject recruitment resulted in more men than women; however, we do not believe this affected the study results.

5. Conclusion

Previously we have shown that the Insole 3 is a valid tool to measure vertical ground reaction force [18]. The current study suggests that the Insole3 is also an accurate method for assessing cadence, gait cycle time, stance time, and to a lesser extent, swing time during slow and moderate-paced walking. Less accurate were speed and stride length, which could be improved upon if the IMU improves distance calculations. Furthermore, taking the mean of multiple walking trials should improve accuracy for speed and stride length. Thus, the device has practical uses in both research laboratories as well as in clinical settings for the measurement of certain STPs. Specifically, data about cadence can be useful in measuring ambulatory performance and intensity of exercise, metrics that could be beneficial to monitor the exercise potential of patients [30,31]. Future work is warranted to investigate cadence, gait cycle time, and stance time using the Insole3 in a variety of clinical populations, particularly in patients with impaired gait. Future studies of the Insole3 or other insole models are also warranted for assessing STPs during other activities such as running, jumping, or squatting.

Funding

This research was funded by the Grainger Chair of the Rush Arthritis and Orthopedics Institute.

Approval

This study was approved by the Rush Institutional Review Board (Rush ORA-12,021,506).

Ethical approval

Work on human beings that is submitted to *Medical Engineering & Physics* should comply with the principles laid down in the Declaration

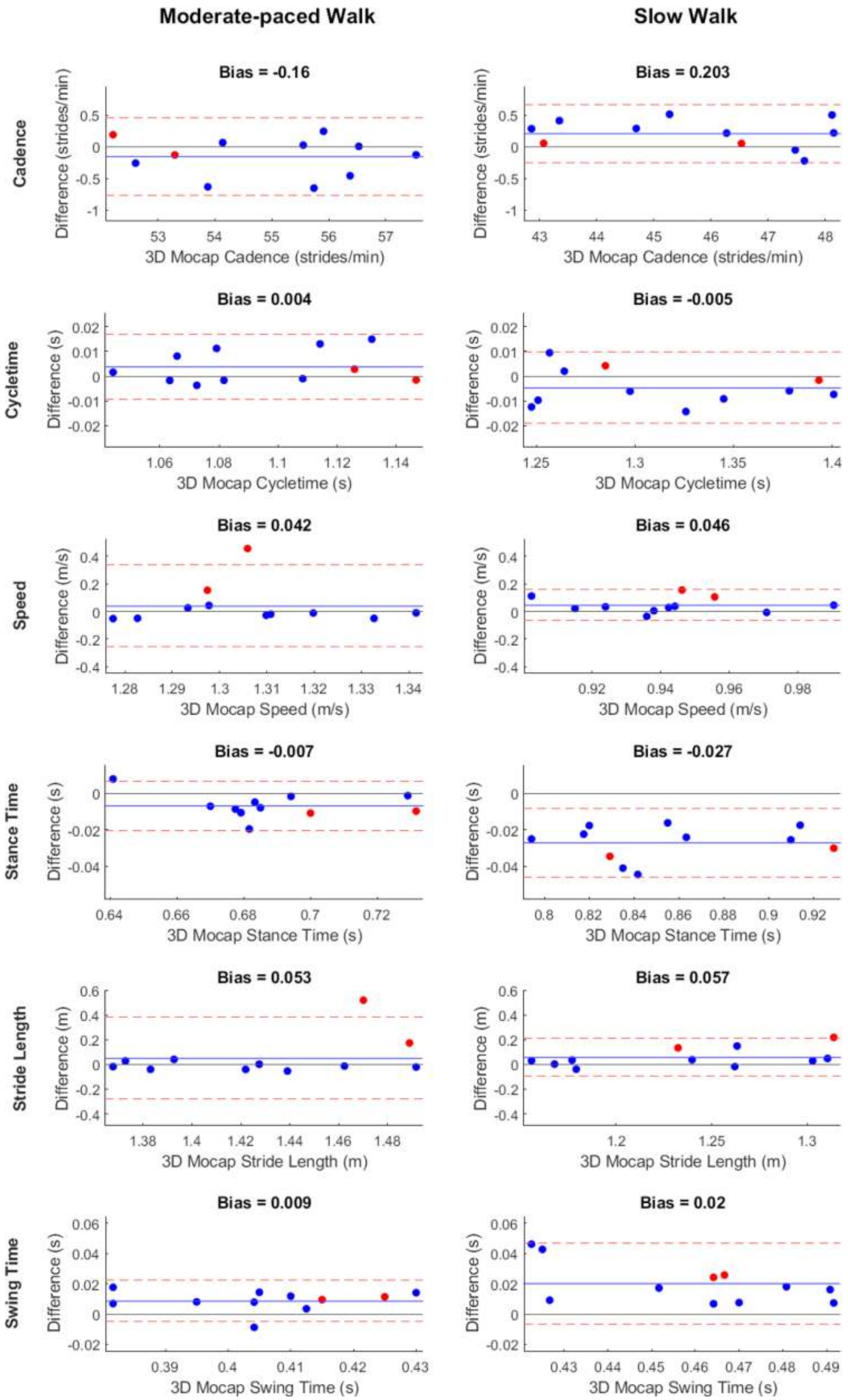

Fig. 3. Modified Bland-Altman plots for agreement between the Insole3 and MOCAP. Each dot represents the mean value for each subject. Red dots indicate subjects 2 and 8, which tended to produce outliers for some variables. The blue solid line indicates the mean of the Insole3. The red dashed lines indicate the limits of agreement (1.96 standard deviations above and below the mean bias for the Insole3).

of Helsinki; Recommendations guiding physicians in biomedical research involving human subjects. Adopted by the 18th World Medical Assembly, Helsinki, Finland, June 1964, amended by the 29th World Medical Assembly, Tokyo, Japan, October 1975, the 35th World Medical Assembly, Venice, Italy, October 1983, and the 41st World Medical Assembly, Hong Kong, September 1989. You should include information as to whether the work has been approved by the appropriate ethical committees related to the institution(s) in which it was performed and that subjects gave informed consent to the work.

Declaration of Competing Interest

We state that we are free of any personal, or business, association(s) that could represent a conflict of interest regarding the article submitted.

Acknowledgments

The authors would like to thank Jade He for providing technical assistance, Leora Cramer for assistance with data acquisition, and Adam Wilson for his input on statistics and assistance with figures.

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