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Original paper

The use of a single inertial sensor to identify stride, step, and stance durations of running gait

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Abstract

Current developments in inertial sensor technology could enable the measurement of running gait outside of the traditional laboratory environment. The purpose of this research was to determine the level of agreement between an inertial sensor and infrared camera based estimates of stride, step, and stance durations across a range of running speeds. An inertial sensor was placed on the sacrum of 10 elite national standard runners, and the stride, step, and stance of running gait were compared. A total of 504 samples were collected and the running velocities stratified into three equal groups of low (10–12 km/h), medium (13–15 km/h), and high (16–19 km/h). A single inertial sensor was found to be suitable for identifying stride duration with Bland–Altman limits of agreement of 95%. The stride data showed agreement at less than 0.02 s for most limits. Agreement for step showed five of the eight upper and lower limits below 0.02 s. The largest differences between both capture methods were for stance. An average bias of 0.0008 s was found and standard error ranged between 0.0004 s and 0.0009 s across all variables. The results from this research found that inertial sensors are suitable to measure stride, step, and stance duration, and provide the opportunity to measure running gait outside of the traditional laboratory.

Keywords: Running; Gait; Instrumentation; Microtechnology; Temporal measures

1. Introduction

The biomechanical assessment of human gait has been conducted in controlled laboratory environments to enable reliable motion analysis.[1–3] This may restrict gait data to a small number of strides in each trial. As such, researchers have used treadmills for longitudinal capture periods.[1,4,5] However, wearing restrictive garments and/or markers, running on a treadmill and attempting to correctly strike a force platform may influence the natural running patterns.[6] The use of accelerometers for analysis of human movement was suggested[7] and recent studies expanded the acceleration concept into inertial sensors measuring gait events when walking.[8] This technology could address the current restrictive issues of assessing human gait only within the confines of the traditional laboratory.

Accelerometers are more accurate at detecting steps taken at low velocities compared to pedometers.[9] In a comparative study, inertial sensors were analysed against kinematic data of walking gait measured by a Vicon® 3D camera system.[10] The authors reported that accelerometers closely matched the camera system across a range of velocities (1.4, 2.1, 2.7, 3.6, and 4.6 km/h). However, higher velocities increased error (<7% of total range) which the authors hypothesised was due to high impact from foot-strike.[10] If a device for measuring running gait that enabled a number of strides to be analysed and did not require treadmill running was found to be suitably accurate, a more reflective measure of an athlete's true running patterns may be possible. This knowledge could enhance the understanding of running gait and provide valuable information that may be useful for injury prevention or performance enhancement.

Inertial sensors have previously been placed in various positions on the body including the lower back region[11,12] during walking analysis. Past inertial sensor gait studies have predominately focussed on walking gait analysis[8,10,13] and have found inertial sensors were accurate in identifying gait events at low walking velocities, but this was not obtained at faster running gait.[8,10] To address this current gap, the aim

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of this research was to determine the agreement between a single inertial sensor and an accepted method to measure running gait specifically; stride, step, and stance durations; and whether this agreement vary with increasing velocity.

2. Methods

Ten national standard runners (six males; four females) volunteered and gave consent to this university ethics approved study which was in accordance with the Statement on Human Experimentation set out by the National Health and Medical Research Council of Australia. The athletes had a mean age of 30.3 (±7.9) years, stature 174.3 (±5.7) cm, and body mass 67.7 (±9.5) kg.

Approximately 1 week prior to the first data capture, athletes were taken through a familiarisation session, this was also used to determine the velocities of three runs. Testing was carried out on a treadmill (TMX425CP, Trackmaster, Full Vision Inc., Kansas, USA) and calibrated within an allowable error range of ±0.2 km/h and ±0.2% grade. Athletes were instructed to run at their self-selected velocity and to limit feedback from the treadmill the instrumentation panel was covered. Athletes returned on three separate occasions for data capture sessions. Each session comprised of three runs of 5 min with 1 min recovery in between. Three velocity groups were chosen for comparison: low (10–12 km/h), medium (13–15 km/h), and high (16–19 km/h). The three runs were 1 km/h below self-selected velocity, at self-selected velocity, and 1 km/h above self-selected velocity. Time for stride, step, and stance were measured in seconds (s) by two formats, an inertial sensor, and infrared cameras. Stride was defined as foot-strike to foot-strike of the same foot, step as foot-strike to foot-strike of the contralateral foot and stance as foot-strike to toe off of each foot.

One inertial sensor (MiniTraqua Version 1, Cooperative Research Centre for Microtechnology, Australian Institute of Sport, ACT, Australia) was used which contained a tri-axial accelerometer (KXM52 – 1050 Kionix, NY, USA) and was calibrated as described elsewhere.[14] The inertial sensor was positioned on the sacrum (S1) and secured by double sided tape directly to the skin-tight running suits worn by the athletes (Online file). To ensure no unwanted movement, elasticised bandage was wrapped around the waist, this also gave support to the reflective markers of the infrared camera system. Orientation of the sensor was to capture data in the three orthogonal planes.

Six infrared cameras (Proreflex MCU 500 Hz, Qualisys Medical AB, Gothenburg, Sweden) and markers, placed as per the Helen Hayes marker set,[15] were used to capture the athlete's head, thorax, pelvis, thigh, shank, and foot anatomical landmarks for 15 s within the last 60 s of each run. The cameras were positioned in a manner that ensured each marker was captured by a minimum of three cameras at any one time. The system was calibrated prior to each testing session.[16]

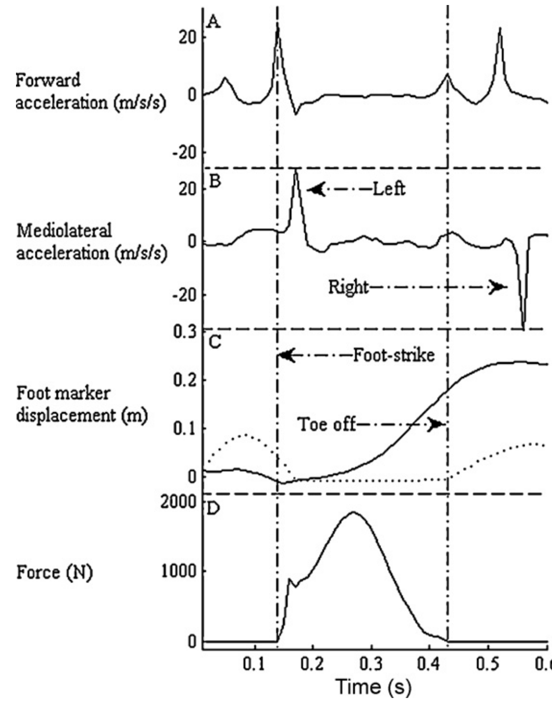

Fig. 1. Typical synchronised gait events of foot-strike and toe off using an inertial sensor (A and B), kinematic camera capture (C), and force platform (D). Depiction in (C); solid profile — = heel, dotted profile . . .. . . = 1st metatarsal.

A pilot study incorporated the inertial sensor, camera system and ground reaction force plate (Bertec Force Plate model 4080, Bertec Corporation, Columbus, USA). The point of synchronisation for the three systems was determined by a vertical movement off and on the force plate. A 6 Hz low pass Butterworth filter was applied to the Qualisys x, y, z coordinate data during signal processing (Visual3D, version 3.90.4, C-Motion Inc., Germantown, USA). Infrared camera detection of foot-strike was the minimum vertical displacement of either the calcaneal marker, or the 1st metatarsal marker, which ever occurred first. This allowed for heel, mid-foot and fore-foot running styles to be identified. Initial upwards movement in vertical displacement of the 1st metatarsal marker identified toe off. Timing of temporal gait events of foot-strike and toe off were obtained from synchronising inertial sensor (Fig. 1A and B), the kinematic camera system (Fig. 1C), with the force plate (Fig. 1D). The agreement between the force plate and the kinematic method in the pilot testing ranged from −0.014 s to 0.006 s (95% limits of agreement), a bias of −0.004 s, standard error of 0.0018, and a high correlation (r = 0.99). No filtering was applied to the inertial sensor data. Foot-strike and toe off were found in anteroposterior accelerations (Fig. 1A). Mediolateral accelerations were used to identify right foot-strike from left foot-strike (Fig. 1B). Acute positive peaks in the anteroposterior graph indicate foot-strike, peaks of smaller magnitude show toe off. Positive peaks in the mediolateral graph coinciding around the positive peaks in the anteroposterior graph indicate left foot-strike. The negative peaks in the mediolateral graph coinciding with the positive peaks in the anteroposterior graph indicate right foot-strike.

Sampling rates for both methods of data capture were 100 Hz which equates to 0.01 s per frame. There were 12 trials in each velocity group. Seven complete right and left strides were assessed within each trial, totalling 168 samples. Previous literature reports that at least three gait cycles be captured to ensure reliability.[17] Reduction of the inertial sensor data was carried out using MATLAB (The MathWorks, Massachusetts USA version 7.5.0.342 (R2007b)). All pair wise differences were plotted as histograms and assumptions for normality were visually assessed and confirmed. Limits of agreement (95%) for the stride, step, and stance durations were determined between the two measurement systems by the Bland–Altman method (Analyse-it Software, Ltd., version 2.11, Leeds, UK). To determine the variation between velocity groups an ANOVA (alpha set at $p = 0.05$) was applied.

3. Results

Agreement between the inertial sensor and the infrared camera methods of measuring stride, step, and stance duration in running are shown in Table 1. Differences between the three duration measures of stride, step, and stance ranged between −0.024 s and 0.023 s (95% limits of agreement). This difference, when sampling at a rate of 100 Hz, is two frames or less (Fig. 2). There was no statistical significant change in these limits of agreement as velocity increased from low, medium to high. Bias was shown throughout the stride, step, and stance duration measures, with an average bias of 0.0008s. Nearly all bias showed the inertial sensor ahead the infrared camera system, demonstrated by negative bias values. The only bias in favour of the infrared camera system

Table 1
Comparisons between the infrared camera and inertial sensor data using Bland–Altman agreements, bias, standard error and correlation.

Velocity	Limits of agreement (s)		Bias (s)	SE (s)	r
	Lower	Upper			
Stride					
Combined	−0.018	0.018	−0.0002	0.0004	0.99
Low	−0.016	0.015	−0.0005	0.0006	0.98
Medium	−0.017	0.020	0.0012	0.0007	0.95
High	−0.021	0.019	−0.0010	0.0008	0.92
Step					
Combined	−0.021	0.018	−0.0008	0.0004	0.95
Low	−0.020	0.018	−0.0007	0.0007	0.93
Medium	−0.021	0.018	−0.0013	0.0008	0.78
High	−0.019	0.019	−0.0004	0.0008	0.76
Stance					
Combined	−0.023	0.020	−0.0014	0.0005	0.93
Low	−0.025	0.022	−0.0011	0.0009	0.91
Medium	−0.020	0.016	−0.0022	0.0007	0.94
High	−0.024	0.023	−0.0008	0.0009	0.90

At 100 Hz, 0.01 s is equal to one capture frame from both units. Negative bias indicates the inertial sensor leads the camera data.

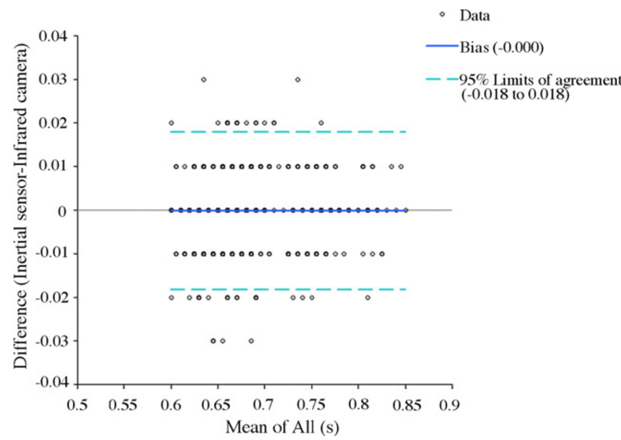

Fig. 2. Typical Bland–Altman plot indicating agreement between an inertial sensor and an infrared camera system.

was the medium stride velocity. Standard error (SE) was also found, ranging between 0.0004 s and 0.0009 s across all running gait variables. The SE for the combined velocity data was approximately half of the individual velocity SE. Correlations of $r = 0.90$ or greater was found in the majority of measures. The medium and high velocity step comparison were the only exceptions, with $r = 0.78$ and $r = 0.76$ respectively.

4. Discussion

The purpose of this research was to determine the agreement between a single inertial sensor and an accepted method to measure running gait specifically; stride, step, and stance durations; and whether this agreement vary with increasing velocity. Agreement for most of the data were less than 0.020 s (two frames at 100 Hz), coupled with small bias (0.0008 s) and SE, and very large to nearly perfect correlations (average $r = 0.91$) demonstrate strong agreement between both methods. There was no statistically significant change in this level of agreement with the changes in velocity, nor were these changes of clinical significance. This small difference between the inertial sensor and infrared cameras is similar to other studies that compared inertial sensors and infrared cameras for walking gait.[10] Sabatini et al. found an inertial sensor placed on one foot could identify walking gait.[13] The current study expanded this finding with one inertial sensor placed on the sacrum satisfactorily identifying the faster running gait stride, step and stance durations. The site of the sacrum has also been used in other gait studies for inertial sensor placement.[5,11,18] Agreement between a single inertial sensor and the infrared camera system, indicates running gait stride, step and stance durations may be measured for extended periods outside of the traditional laboratory setting.

Strong agreement between both methods was shown in the stride data along with minimal bias present. This was reflected across all three velocity groups and the combined velocity group. Stride is an important phase to identify due to it being the starting point for most gait assessment along with assistance in structuring step and stance phase detection.[18] A similar agreement was also found for step, with large correlations between both methods. This finding is consistent with walking studies that identified steps at low velocities,[9] but is in contrast to faster velocity studies that found up to 7% error in step identification.[10] This improved measure at faster velocities is attributed to the sacrum placement of the sensor in the current study, compared to the lower limb sensor placement in the earlier study. Slightly less agreement was found for stance with most of the data ranging from exactly to just over 0.020 s (two capture frames difference) across all velocity groups.

Events identified by the inertial sensor were generally easily identifiable with foot-strike defined by the anteroposterior acceleration spike (Fig. 1). A smaller spike defined toe off. Across most stance groups, toe off presented as an earlier bias in the sensor data than the camera data which may be related to the body unweighting earlier. The gait events via the inertial sensor method were identified within the anteroposterior accelerations, whilst the mediolateral accelerations were used to identify whether the events were from the left or right side. This combination of two different inertial sensor profiles was necessary for identifying gait events and is important when measuring stride, step, and stance. The requirement to use multiple inertial measures to identify gait events is similar to other studies.[8] The identification foot-strike events and from which side via the inertial sensor, are displayed by the distinct peaks shown in Fig. 1A and B. This profile is also similar to that found in studies measuring walking gait accelerations.[18]

This current study measured running gait on a treadmill. Other studies found no significant differences when comparing overground and treadmill running in kinematic variables of the lower limbs, after 6 min of familiarisation.[19,20] These findings in conjunction with findings from the current study indicates the collection of running gait data can be achieved in typical situations for running.

5. Conclusion

This study found a single inertial sensor positioned at the sacrum is suitable for identifying stride, step, and stance duration of running gait with suitable levels of agreement when compared to an infrared based system. Changes in a narrow range of running velocities did not influence the levels of agreement between the two measures.

Practical implications

- The wireless and small size of these units enable gait data to be collected without the restrictions associated with a laboratory.
- Longitudinal data capture of running gait may be possible.
- During training a single inertial sensor can be used to provide feedback on stride, step, and stance durations.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsams.2009.01.005.

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