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ORIGINAL RESEARCH

VALIDATION OF A SINGLE INERTIAL SENSOR FOR MEASURING RUNNING KINEMATICS OVERGROUND DURING A PROLONGED RUN

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ABSTRACT

Introduction: The purpose of this study was to validate acceleration data from a single inertial sensor containing a tri-axial accelerometer, whilst running overground during a prolonged run against a motion analysis system.

Methods: An inertial sensor was placed on the low back of 10 runners who performed an 8 km run on a treadmill. To provide validation of the sensor, data were collected as runners ran along a runway through a motion analysis system at the beginning and throughout the run.

Results: High levels of agreement between the two systems were found in the craniocaudal and mediolateral acceleration, with anteroposterior having the least agreement with greatest Typical Error of the Estimate (0.66 sample points). Very high to extremely high correlations across all testing times were found in all three directions of accelerations (r=0.75 to 0.95). Heel strike and toe off events were identified in anteroposterior and craniocaudal acceleration, with high levels of agreement and extremely high correlations (r=0.99) between the two systems. Minimal variation and change in agreement and correlation between the data at each testing time were found.

Discussion: This study provides evidence that a single inertial sensor placed on the low back is valid for measuring three-dimensional acceleration in overground running during a prolonged run. Further analysis identified specific events of heel strike and toe off and were comparable between the two systems. The minimal variation and change in agreement between the two systems during the run indicates the adherence method of the inertial sensor was suitable.

Conclusions: The results of this study indicate that data collected from a single inertial sensor is highly correlated with simultaneous data collected using a motion analysis system, and has the capability to identify heel strike and toe off events in overground running throughout a prolonged fatiguing run.

Keywords: accelerometer, sensor, running, motion analysis.

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INTRODUCTION

Long distance running is a prolonged repetitive activity and fatigue causes changes in running kinematics[1]. To date, the assessment of running kinematics during prolonged runs have typically been conducted on treadmills using motion analysis systems and ground reaction force measurements[2,3,4]. While these systems provide accurate measurements they are restricted to laboratories, only providing snippets of information and not allowing for continuous analysis of prolonged running in outdoor overground environments. Furthermore, biomechanical differences between treadmill and overground running have been reported[5,1]. Strohrmann et al.[1] reported differences in step frequency and vertical displacement during prolonged treadmill running but not during overground running, while Sinclair et al.[5] found differences in lower limb kinematics between short overground and treadmill steady-state runs. These findings suggest that treadmill running may not be comparable to overground running, and highlights the need to use technology that is capable for the analysis of running in field conditions. Additionally, due to long distance running being a prolonged repetitive activity, the technology needs to be capable of continuously collecting data over a prolonged time.

The use of inertial sensors are becoming increasingly popular for the analysis of human movement. They small, lightweight and practical, with the capability to collect continuous three-dimensional acceleration data to measure human movement in field conditions[6,1,7,8]. A single inertial sensor placed on the low back provides a simple and effective method to examine movement near the centre of mass (COM)[6]. Not only is a low back mounted position the closest external point to the whole body COM, it is the lowest point where a single measuring device can monitor left and right lower limb kinematic data, such as heel strike and toe off. Furthermore, this position would most likely be the best position to measure contralateral changes in gait symmetry[9] that may present in running gait due to variables such as fatigue during prolonged running. Studies have used the COM placement method to assess running kinematics during treadmill running[6,7] and short overground running[8]. MacGregor et al.[7] demonstrated that a single inertial sensor placed on the low back was capable of accurately and reliably estimating energy expenditure and running mechanics during treadmill running and found differences between trained and untrained runners. Using the same sensor location Le Bris et al.[8] found increases in mediolateral acceleration data in runners during a short exhaustive overground run indicating alterations in running patterns with fatigue. While these studies demonstrate that a single inertial sensor placed on the low back has the capability to measure human movement near the centre of mass, currently there is a paucity of research using this method to assess kinematics during overground running over a prolong run.

To ensure that inertial sensors provide accurate information in overground running during a prolonged run, validation against a criterion instrument or measure is required[10]. Laboratory based three-dimensional motion analysis systems have been used for gait analysis and are a well-established criterion for the analysis of movement[11,12,13]. Recent studies have validated the use of an inertial sensor placed on the low back for measuring gait events and vertical acceleration of the COM against a motion analysis system during short treadmill runs[9, 14]. However, no studies have validated the use of a single inertial sensor against a motion analysis system to assess kinematic variables in overground running during a prolonged run. Such a validation would benefit from further research.

While previous research has validated temporal gait kinematics in running[14], this was not for extended durations. While Lee et al[9] reported that inertial sensor data alterations in left and right running symmetry with changes in speed, the authors did not report whether fatigue had the same detectable effect on inertial sensor output. Once validated, this may provide unique opportunities for in-field, real environmental assessment of prolonged running gait kinematics that may not be achievable in simulated laboratory settings. To determine whether kinematic measures and changes reported in the inertial sensor studies[9, 14] areneeded to determine kinematic changes over extended time periods and provide important information about fatigue-related kinematic changes that occur during long distance running. This information can then be utilised to improve understanding of changes that may be detrimental to performance or increase the risk of injury.

If a single inertial sensor placed on the low back is shown to be valid, then more advanced analyses may be obtained. These include heel strike and toe off events in the gait cycle. These gait events can then be used for further analysis for measuring contact time, flight time, stride and step durations[14]. This provides relevant information on a runner's spatiotemporal characteristics, and provides trainers and runners with relevant information on a runner's running style under field conditions[15].

The ability for sensors to remain in place on the trunk with movement has been suggested to contribute to errors in acceleration data[11,16]. During a prolonged run, there is increased opportunity for alteration in the position of the sensor compared to a short run, leading to an increased risk of error in the acceleration data. Again highlighting the need to validate inertial sensor data capture during a prolonged run.

Therefore, the aims of this study were to: 1) compare acceleration data collected using an inertial sensor with a laboratory motion analysis system in overground running during a prolonged run, and 2) determine whether specific events in the running gait cycle (heel strike and toe off) were identified consistently by both data collection methods.

METHODS

Participants

Ten (six male; four female) recreational runners (27.5 ± 9.5 years, 175.8 ± 8.1 cm, 69.5 ± 11.8 kg) were recruited. Participants were included if they ran at least 30 km per week (average 52.5 ± 12.75 km/week), were injury free at time of testing, and had no lower extremity abnormalities that affected their gait. The study was approved by the James Cook University Human Research Ethics Committee (H5217).

Procedures

Participants wore clothing that allowed their lower back to be exposed. The sensor was adhered using double-sided tape directly to the skin of the runner's low back, and secured with an elastic bandage that was wrapped over the sensor and around the waist[9,14]. Reflective markers were adhered with double-sided tape on the sensor and on the midpoint of the rear foot (calcaneal) and the forefoot (distally on the 1st metatarsal) of the participant's shoes.

A sport specific inertial sensor was used[17] and calibrated using software from a custom toolbox[18]. The inertial sensor (52 x 33 x 10 mm, mass 21 g) comprised of a tri-axial accelerometer (sampling at 100 Hz, saturation at 8*g*)[19]. The three-dimensional axes of the sensor were manually orientated with the anatomical (orthogonal) axes of the craniocaudal (X), mediolateral (Y) and anteroposterior (Z) directions with the participant standing in a static position.

The kinematic three dimensional positioning data of the reflective markers were recorded using a 12 infrared camera motion analysis system and supporting software (NEXUS v1.8, Vicon Motion Systems Ltd. UK) operating at 100 Hz. Calibration of the system and capture zone was carried out using the calibration wand as per the manufacturer's instructions.

Running Preparation

Prior to commencing the running protocol, participants were familiarised with running on the treadmill, how to safely dismount the treadmill and run along the runway of the motion analysis laboratory. Participants completed a five minute warm-up on the treadmill prior to commencement of data collection.

Running Protocol

The treadmill gradient was fixed at 1% to compensate known variances between treadmill and overground running and ensure energy expenditure was close to the participant's experience when running on level surfaces[20]. Following warm-up, participants ran along the 50 m runway of the motion analysis laboratory. This was repeated on the return run. Overground running data were collected during this run using a 10 m long infrared camera capture field situated mid-way along the runway. Participants then mounted the treadmill to begin the 8 km run, and instructed to run at a self-selected pace typical of their aerobic training for the entire 8 km. Participants dismounted the treadmill after 2 km, 4 km, 6 km, and 8 km to run along the runway. Participants were only off the treadmill for a short period of time to run through the runway once and then remounted the treadmill to continue the prolonged run. During each runway run, overground data within the infrared capture field was collected simultaneously via the inertial sensor and the motion analysis system.

Synchronisation of Measurements

Synchronisation of the inertial sensor and motion analysis system data were achieved using first contact with the ground within the infrared camera motion analysis system's capture field. Both systems' recording commenced before participants entered the camera capture field. Strides were counted from the commencement of the run to the first contact within the marked boundary of the capture field. From these synchronised data points acceleration changes at any given point in any plane was compared for agreement between the two systems.

Signal Processing

Heel strike and toe off events were identified in raw sensor data to ensure no loss or timing shift from filtering. All three channels were used to identify both events. Heel strike was identified at the point where the Z acceleration began increasing towards its large impact peak (Figure 1). For toe off, an algorithm detected the zero acceleration crossover in the X acceleration data[15]. The same events in the motion analysis system were identified in the system's signal processing function prior to differentiation and filtering. For the motion analysis system, heel strike was deemed as the lowest vertical displacement of the calcaneal positioned marker and toe off was the first vertical displacement of the 1st metatarsal marker. All participants were identified during the warm up as heel strikers.

The motion analysis system data were collected as displacement relative to the global origin. Double derivative calculation was performed to convert it to acceleration and allow direct comparison to the sensor acceleration data and reflective marker positioned on the low back. Inertial sensor data were recorded as millivolts and were calibrated to produce gravitational (*g*) scale output. All data were trimmed to synchronisation points.

The inertial sensors recorded acceleration data from the three orthogonal axes.

The effect of gravity acting on the sensor was obtained by low pass filtering the data at 0.5 Hz[17]. This vector was then removed from the raw data. A 10 Hz low pass Hamming Filter was applied removing high frequency noise in line with frequency calculation methods previously reported[14]. The primary purpose was to filter noise and impact peaks in order for comparisons to be made with the infrared camera system comparison. The infrared camera system was filtered using the system's dynamic gait filtering within its processing capabilities. The synchronisation points allowed for both systems' data to be aligned for comparisons of acceleration magnitudes of the sensor and reflective marker. From this, measures of agreement and correlation were calculated. Additionally, overlay plots of the trimmed data sets were generated, providing visual demonstrations of outputs.

Statistical Analysis

Agreement between the inertial sensor data and motion analysis system data were conducted using the Typical Error of the Estimate (TEE)[21]. The error of the estimate is the amount by which the sensor differed from the motion analysis system. A TEE analysis uses the units of the dependent variable, in this case sample points. The closer to parallel and the narrower the spread of data,

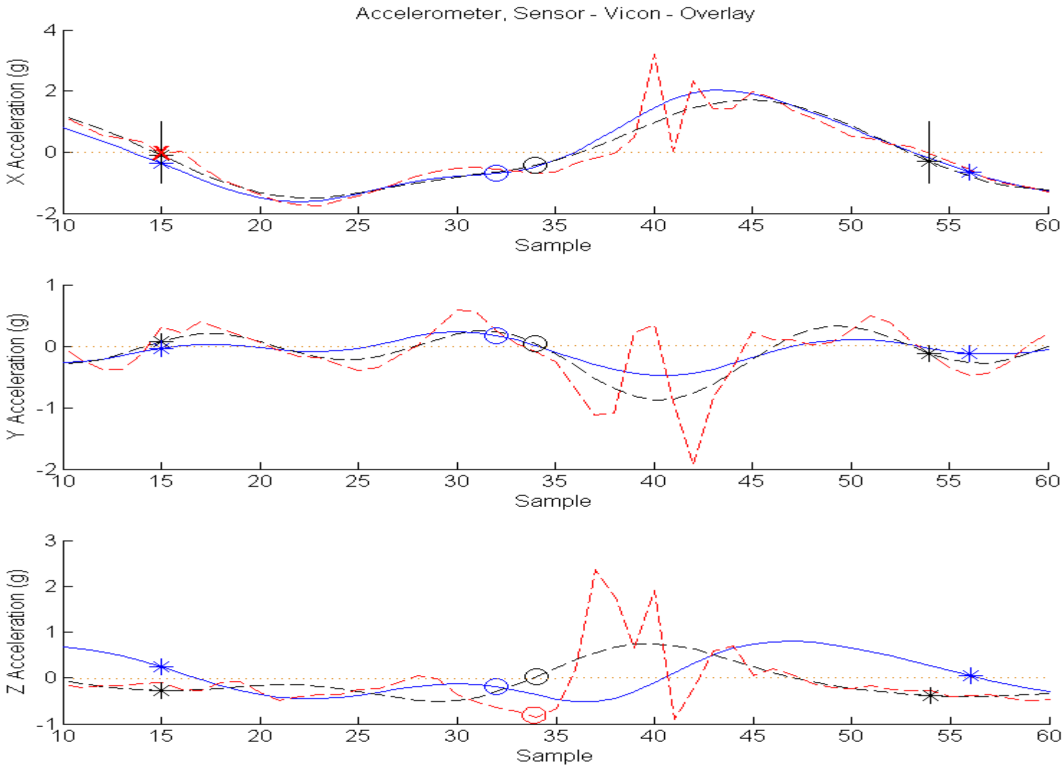

Figure 1: Typical heel strike and toe off gait events detected in the inertial sensor and Vicon motion analysis system. X acceleration = craniocaudal; Y acceleration = mediolateral; and Z acceleration = anteroposterior. The Y axis depicts the capture frames which equates to 100 samples equalling 1 second. The filtered data has been included to display the levels of agreement between the two systems (dashed black line = sensor data and solid blue line = Vicon data). Heel strike was identified in the raw data (dashed red line) of Z acceleration data and toe off in the raw data of X acceleration. Symbol legend: blue circle = heel strike in Vicon data, red circle = identified heel strike in raw data in Z acceleration, black circle = equivalent time point (to red circle time point) in filtered sensor data, Blue asterisk = Vicon toe off, Red asterisk = identified toe off in raw sensor data in X acceleration, Black asterisk = sensor toe off.

indicates how well the inertial sensor data aligns with the motion analysis system. The TEE and bias results were interpreted using the Hopkins modified Cohen scale: <0.20, trivial; 0.2-0.6, small; 0.6-1.2, moderate; 1.2-2.0, large; >2.0, very large. Confidence limits were set at 95%[21]. Residuals were used to describe the spread of data between the upper and lower confidence limits. The smaller the residual, the closer the agreement between both systems and the greater confidence of accuracy of the relationships. The TEE plots were used to visually display the data differences between the systems.

Correlation analyses were performed to determine the relationship between acceleration and motion analysis data using Pearson's R correlation. The correlation classifications were interpreted using the Hopkins[22] scale: 0.01-0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, high; 0.7-0.9, very high; 0.90-<1.0, extremely high; 1, perfect.

RESULTS

The TEE and correlations have been presented for each acceleration direction and motion analysis system data (Table I). Comparisons were on all data sample points (*n*=6163) detected inside the infrared capture field.

Craniocaudal Acceleration

The correlation was extremely high, averaging 0.95 across all testing times. The average TEE across all captures was small at 0.31 sample point. The TEE plot highlights the strong agreement

Table 1: Typical Error of the Estimate and correlation between inertial sensor acceleration data and infrared camera system data. Residual data is the difference between the upper and lower confidence limits (CL). Typical Error of the Estimate units of measure are sample points.

Typical Error of the Estimate					Correlation			
Distance	TEE	Upper CL	Lower CL	Residuals	r value	Upper CL	Lower CL	Residuals
Craniocaudal Acceleration								
0 km	**0.28**	0.29	0.27	0.017	**0.96**	0.96	0.96	0.007
2 km	**0.32**	0.33	0.31	0.020	**0.95**	0.95	0.94	0.009
4 km	**0.32**	0.33	0.31	0.022	**0.95**	0.95	0.94	0.010
6 km	**0.31**	0.33	0.30	0.024	**0.95**	0.95	0.94	0.011
8 km	**0.30**	0.31	0.29	0.021	**0.95**	0.96	0.95	0.009
All runs	**0.31**	0.31	0.30	0.009	**0.95**	0.95	0.95	0.004
Mediolateral Acceleration								
0 km	**0.55**	0.57	0.54	0.033	**0.83**	0.85	0.82	0.026
2 km	**0.45**	0.47	0.44	0.028	**0.89**	0.90	0.88	0.018
4 km	**0.52**	0.54	0.51	0.036	**0.85**	0.86	0.84	0.027
6 km	**0.53**	0.56	0.52	0.040	**0.85**	0.86	0.83	0.030
8 km	**0.44**	0.46	0.43	0.031	**0.85**	0.91	0.89	0.019
All runs	**0.50**	0.50	0.49	0.015	**0.90**	0.87	0.86	0.010
Anteroposterior Acceleration								
0 km	**0.64**	0.65	0.62	0.038	**0.77**	0.79	0.76	0.034
2 km	**0.69**	0.71	0.67	0.043	**0.72**	0.74	0.70	0.042
4 km	**0.64**	0.66	0.62	0.044	**0.77**	0.79	0.75	0.040
6 km	**0.67**	0.70	0.65	0.050	**0.74**	0.77	0.72	0.048
8 km	**0.65**	0.68	0.63	0.045	**0.76**	0.78	0.74	0.042
All runs	**0.66**	0.67	0.65	0.020	**0.75**	0.76	0.74	0.019

between both systems (Figure 2). The comparison prior to commencing the treadmill run (0 km) showed the least error (0.28 sample point). The error was also small at 2 km, 4km, 6 km and 8 km comparison and correlation very high.

Mediolateral Acceleration

The correlation was high, averaging 0.87 across all testing times, and average TEE across all captures was small at 0.50 sample point. The TEE plot highlights a high level of agreement (Figure 3). The comparison at the end of the 8 km run showed a very high correlation (r=0.90) and least error (0.44 sample point).

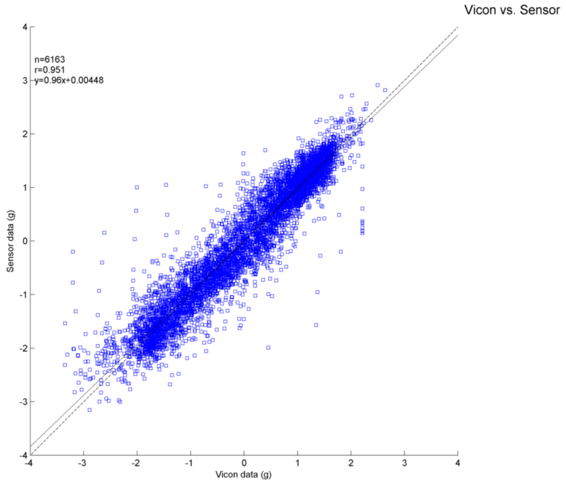

Figure 2: Comparison of craniocaudal acceleration data collected using inertial sensors to the criterion measure of an infrared camera system. The solid line is the mean of inertial sensor data and dashed line, the criterion.

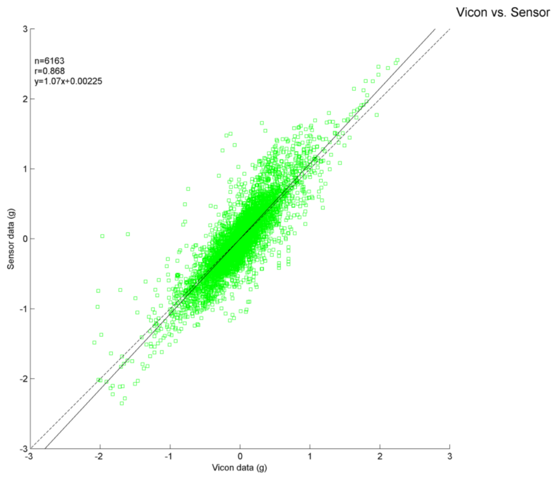

Figure 3: Comparison of mediolateral acceleration data collected using inertial sensors to the criterion measure of an infrared camera system. The solid line is the mean of inertial sensor data and dashed line, the criterion.

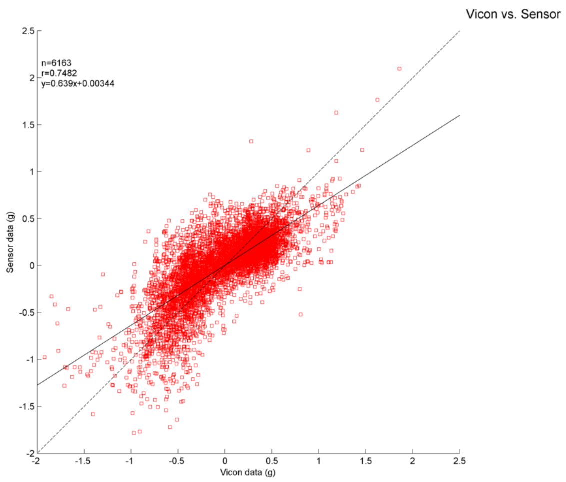

Figure 4: Comparison of anteroposterior acceleration data collected using inertial sensors to the criterion measure of an infrared camera system. The solid line is the mean of inertial sensor data and dashed line, the criterion.

Anteroposterior Acceleration

The correlation was high averaging 0.75 across all testing times. Anteroposterior acceleration had the greatest error, however it was at the lower end of moderate (0.66 sample point). The comparison at 0 km and 4 km the end of the 8 km run showed the highest correlation (r=0.77) and least error (0.64 sample point).

The TEE plot shows the lower agreement between the two systems (Figure 4).

Gait events

Heel strike and toe off were primarily identified in the raw data in the anteroposterior and craniocaudal acceleration data, respectively (Figure 1). Heel trike corresponded to commencing the upward climb in the anteroposterior acceleration data, and toe off corresponded to the crossing of the craniocaudal acceleration at zero of the downward curve. Average variation in the heel strike event between both systems were shown to be 0.15 sample point, which is equivalent to 0.002 seconds (s), or less than the capture rate (100 Hz). Average variation in the toe off event were shown to be 0.013 s (1.3 sample points). The range of the differences were between -0.04 s and 0.05 s. The TEE was shown to be trivial at 0.08 sample point for both heel strike and toe off. The correlation was very high (r = 0.99) for both gait events.

DISCUSSION

The study's aim was to compare acceleration data collected from a single inertial sensor with a motion analysis system during overground running under fatigue conditions, and determine whether specific events in the running gait cycle were identified consistently by both data collection methods. This study provides evidence that a single tri-axial inertial sensor placed on the low back is valid for measuring three-dimensional acceleration and identifying specific events in overground running during a prolonged fatiguing run. Craniocaudal and mediolateral acceleration data demonstrated the best accuracy of running kinematics with high levels of agreement and correlations between data from both systems. Anteroposterior acceleration displayed less agreement between both, however a high level of correlation indicates a relationship between the two systems of measure. Specific events of heel strike and toe off were comparable and identifiable using anteroposterior and craniocaudal acceleration data, respectively.

The craniocaudal acceleration data were found to have the lowest error and very high correlations at all testing times, therefore strong agreement between the two systems can be reported. This concurs with previous research that reported similar outcomes when using a low back mounted sensor comparing craniocaudal acceleration to a motion analysis system during treadmill running[9]. The comparisons in the mediolateral direction had slightly higher error than the craniocaudal acceleration. However, differences were small when referenced to the modified Cohen scale, and very high correlations between comparison data were found across all testing times. This is supported by the narrow spread of the data (Figure 2), indicating high levels of agreement between the two systems in mediolateral acceleration. Research by Lee, Mellifont and Burkett[14] validated mediolateral data for identification between left and right steps when identifying spatiotemporal kinematics during treadmill running with the sensor also placed on the low back. Clear positive and negative peak signals in the mediolateral acceleration data were detected that occurred just following heel strike. Outcomes reported here and that found in previous research[9, 14] indicate that craniocaudal and mediolateral accelerations are valid measures of running kinematics.

The anteroposterior acceleration data showed least agreement of the three orthogonal planes, with moderate error found. While it would be assumed that all three channels of data should compare similarly an agreement, this was not seen in this study (Figures 1, 2, and 3). The reduced agreement in the anteroposterior acceleration may be attributable to the infrared camera system measuring positional displacement change of participants while running forward, which is continual in the direction of travel. Anteroposterior acceleration in running is in the forward direction which has a lower magnitude than the impact peaks, therefore, directional acceleration measured by the sensor may be blending into ground impact acceleration. The blending of forward and heel strike accelerations may explain why the direction of movement measured by the inertial sensors provides a variation to data collected by the motion analysis system. Craniocaudal and mediolateral acceleration measurements are generally from one source (impact acceleration) unlike the combination of forward momentum acceleration and temporal kinematics acceleration typically found in anteroposterior data. Craniocaudal and mediolateral directional motions had cyclically repeating accelerations with clear peaks which may explain the increased validity in these directions. Another possibility for variation is that acceleration of forward movement is less than gravity, which inertial sensors simultaneously measure, while the infrared camera system is not. While gravity is not measured in the anteroposterior direction, it affects the forward movement readings. Therefore, the effect of gravity should be removed before comparative agreement assessments. Although the process used to remove gravitational data was not perfect (due to the dynamics attributed to the movement), it was the best known method[23]. It involved low pass filtering to find an approximate orientation with respect to gravity acting on the sensor. The result provides the constant gravity vector relative to the sensor. This vector is then removed from the raw data. This technique is constant and very low frequency accelerations not attributable to gravity are also removed, resulting in difficulties removing gravity effects without affecting kinematic accelerations smaller than 1 *g*.

While agreement was least in anteroposterior acceleration data, the very high correlations found indicates a relationship between the anteroposterior data collected by the two systems. Therefore, data collected by the sensor in this direction may still be considered an acceptable measurement of overground running kinematics.

The identification of gait events using the inertial sensors were found in the raw data of anteroposterior and craniocaudal acceleration and demonstrated very high correlation with the motion analysis system. Heel strike corresponded to the beginning of the upward peak in anteroposterior acceleration, and toe off was identified when craniocaudal acceleration crossed at zero of the downward curve. This is similar to Auvinet et al.[15] who identified heel strike and toe off in these acceleration channels in short duration overground runs using an accelerometric sensor attached to the low back. Auvinet et al.[15] used filtered data to identify the gait events, while this current study found clearer points in the raw data. The differences between studies using filtered and raw data may be due to the system used that the events were compared to. Auvinet et al.[15] compared sensor data to a video camera analysis, while this study used a motion analysis system, and this may have accounted for the differences in the acceleration data used. Future research using a similar method as in this current study will use the raw data for gait event analysis as the study findings indicate that a low back mounted sensor has the capability to identify heel strike and toe off gait events during overground running during a prolonged run. While there were variations between data from the three channels of capture, an important finding was that little change in agreement occurred between both systems at each testing session during the 8 km run. This indicates that the adherence method used in this study allowed the inertial sensor to remain in place throughout the prolonged run. It has been suggested that sensor movement may contribute to error[11, 16], however, this was not the case in this study.

A limitation of this study was that data were collected while running along a short runway. Although, there was agreement between the two systems, the running kinematics on such a runway may not entirely replicate kinematics of prolonged overground running.

CONCLUSIONS

Three-dimensional acceleration data collected from an inertial sensor in overground running during a prolonged run is highly correlated with simultaneous data collected using a motion analysis system. To the authors' knowledge, no researchers have validated inertial sensors in this context. Furthermore, specific events of heel strike and toe off in the gait cycle are clearly identifiable from the inertial sensor in the anteroposterior and craniocaudal acceleration data. Little change in variation between the inertial sensor and motion analysis data throughout the prolonged run indicates a suitable method of adherence of the sensor. This study supports future use of a single inertial sensor positioned at the low back to assess kinematics during prolonged overground running.

PRACTICAL APPLICATIONS

A single inertial sensor placed on the low back can be used to assess three-dimensional acceleration data during overground running under fatigue conditions,

Further analysis of the data can be used to identify heel strike and toe off events in the gait cycle during overground running.

REFERENCES

1. Strohrmann, C., Harms, H., Kappeler-Setz, C., & Troster, G. (2012). Monitoring kinematic changes with fatigue in running using body-worn sensors. *IEEE Trans Inf Technol Biomed, 16*, 983-990.
2. Koblbauer I., van Schooten, K., Verhagen, E., & van Dieen, J. (2014). Kinematic changes during running-induced fatigue and relations with core-endurance in novice runners. *Journal of Science and Medicine in Sport, 17,* 419-424
3. Dierks, T.A., Davies, I.S., & Hamill, J. (2010). The effects of running in an exerted state on lower extremity kinematics and joint timing. *Journal of Biomechanics, 43,* 2993-2998.
4. Gerlach, K.E., White, S.C., Burton, H.W., Dorn, J.M., Leddy, J.J., & Horvath, P.J. (2005). Kinetic changes with fatigue and relationship to injury in

female runners. *Medicine and Science in sports & Exercise, 37,* 657-663.
5. Sinclair, J., Richards, J., Taylor, P., Edmundson, C., Brooks, D., & Hobbs, S. (2013). Three-dimensional comparison of treadmill and overground running. *Sports Biomechanics, 12*, 272-282.
6. Kobsar, D., Osis, S., Hettinga, B., & Ferber, R. (2014). Classification accuracy of a single tri-axial accelerometer for training background and experience level in runners. *Journal of Biomechanics, 47,* 2508-2511
7. McGregor, S., Busa, M., Yaggie, J., & Bollt, E. (2009). High Resolution MEMS Accelerometers to Estimate VO2 and Compare Running Mechanics between Highly Trained Inter-Collegiate and Untrained Runners. *PLoS One, 4,* e7355.
8. Le Bris, R., Billat, V., Auvinet, B., Chaleil, D., Hamard, L., & Barrey, E. (2006). Effect of fatigue on stride pattern continuously measured by an accelerometric gait recorder in middle distance runners. *Journal of Sports Medicine & Physical Fitness, 46,* 227-231.
9. Lee, J., Sutter, K., Askew, C., & Burkett, B. (2010). Identifying symmetry in running gait using a single inertial sensor. *Journal of Science and Medicine in Sport, 13*, 559-563.
10. George, K., Batterham, A., & Sullivan, I. (2003). Validity in clinical research: a review of basic concepts and definitions. *Physical Therapy in Sport 2003, 4*, 115-121.
11. Wundersitz, D., Gastin, P., Richter, C., Robertson, S., & Netto, K. (2015). Validity of trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running. *European Journal of Sport Science,* 5, 382-390.
12. Chung, P.Y.M., & Ng, G.Y.F. (2012). Comparison between an accelerometer and a three-dimensional motion analysis system for the detection of movement. *Physiotherapy, 98*, 256-259.
13. Lee, H.K., Cho, S.P., You, J.H., & Lee, K.Y. (2007). The concurrent validity of the body center of mass in accelerometric measurement. *In: Proceedings of the 29th Annual International Conference of the IEEE, EMBS,* 23-26.
14. Lee, J., Mellifort, R., &Burkett, B. (2010). The use of a single inertial sensor to identify stride, step, and stance durations of running gait. *Journal of Science and Medicine in Sport, 13*, 270-273.
15. Auvinet, B., Gloria, E., Renault, G., & Barrey, E. (2002). Runner's stride analysis: comparison of kinematic and kinetic analyses under field conditions. *Science and Sports, 17*, 92-94.
16. Wundersitz, D., Netto, K., Aisbett, B., & Gastin, P. (2013). Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. *Sports Biomechanics,* 12, 4013-412.
17. Davey, N., Anderson, M., & James, D. (2008). Validation trial of an accelerometer-based sensor platform for swimming. *Sports Technology, 4-5,* 202-207.
18. James, D., & Wixted, A. (2011). ADAT: A Matlab toolbox for handling time series athlete performance data. *Procedia Engineering, 13*, 451-456.
19. James, D., Leadbetter, R., Madhusudan, R.N., Burkett, B., Thiel, D., & Lee J. (2011). An integrated swimming monitoring system for the biomechanical analysis of swimming strokes. *Sports Technology, 43*, 141-150.
20. Jones, A., & Doust, J. (1996). A 1% treadmill grade most accuratelt reflects the energetic cost of outdoor running. *Journal of Sport Science, 14*, 321-327.
21. Hopkins, W. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*, 1-15.
22. Hopkins W. (2010). Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience, 14*, 49-57.
23. Wixted, A., Thiel, D., Hahn, A., Gore, C., Pyne, D., & James, D. (2007). Measurement of energy expenditure in elite athletes using MEMS-based triaxial accelerometers. *IEEE Sensors Journal, 7*, 481-488.