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Title: Validation of trunk mounted inertial sensors for analysing running biomechanics under field conditions, using synchronously collected foot contact data.

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Abstract:

The biomechanical evaluation of elite athletes often requires the use of sophisticated laboratory-based equipment that is restrictive, cumbersome, and often unsuitable for use in a training and competition environment. Small, low-mass unobtrusive centre-of-mass triaxial accelerometers can be used to collect data but may not reveal all the information of interest. This validation of centre-of-mass triaxial accelerometry uses previously reported [*references removed*] synchronously collected foot-contact information from in-shoe pressure sensors. A qualitative assessment of the system output indicates that the centre-of-mass acceleration provides valuable insight into the use of accelerometers for investigating the biomechanics of, in this case, middle distance runners.

Introduction:

Historically, collection of data from athletes engaged in strenuous exercise has occurred primarily in laboratory settings, because of the need to use equipment that is not easily transferable to the field. However, laboratory measurements have only limited value because exercise machines do not perfectly simulate natural activities, and it is difficult to replicate outdoor environmental conditions. In the case of athletes, laboratory tests are typically quite infrequent, further restricting the amount of useful information that can be gained.

The use of wearable measurement systems that do not unnecessarily encumber or constrain the individual's natural environment, allow for the monitoring of on-field, real time and day-by-day performance of athletes.

In this paper, the output of inertial sensors is compared to concurrently collected in-shoe pressure. This gives the accelerometer data a reference to flight and stance phases as well as a comparison to ground contact forces.

The purpose of this technical note is to report on general findings associated with the simultaneous collection of such information during middle distance running.
Auvinet et al. [3] used an accelerometric device to compare the kinematics and kinetics of seven elite middle distance runners under field conditions. The authors found that characteristic patterns in each accelerometric axis could be used to identify initial contact, mid-stance and toe-off points along with contra-lateral foot contacts. Further, without making direct comparisons the authors concluded, on a qualitative level, that the vertical and anterior-posterior acceleration signals agreed with the waveform of the respective components of ground reaction force measured by a force platform system.

Using a similar inertial measurement apparatus Barrey et al. [4] identified quantitative relationships between temporal and kinetic locomotory variables of race horses at the gallop and how these variables related to the horses' racing ability.

In-shoe pressure distribution measurements have been used extensively to investigate the interaction between human body, footwear and ground in running. Hennig and Milani [5] reviewed the changes in discrete pressure distribution measurements as a function of running speed and footwear properties. Eight discrete piezoceramic transducers were positioned underneath the major anatomical support structures of the foot. Simultaneously, ground reaction forces and acceleration along the tibial axis was measured with a low mass accelerometer. The authors found that the first ray of the foot, composed of the first metatarsus and hallux, was identified as one of the major load bearing structures during the push-off phase.

Billing et al. [1] used low mass in-sole sensors to collect ground reactions forces transmitted through the foot-shoe-ground interface and trunk mounted triaxial accelerometers to capture acceleration. They then combined the data from the different sensors via neural networks to predict the three dimensional ground reaction forces [2].

Lee et al. [6] combined in-shoe accelerometers with centre-of-mass accelerometers, extracting ground contact references from the in-shoe accelerometers and using these references to frame the centre-of-mass accelerometer data.

This paper reviews the combination of in-sole pressure sensing and synchronously collected centre-of-mass accelerometry to validate the centre-of-mass accelerometry as a tool for the investigation of causal biomechanical relationships. This paper presents graphical data from two middle distance runners and makes interpretations of the graphical material. Measurable parameters such as step frequency, race and split timing, along with inter-subject comparison, were used to frame the interpretation.

Methodology:

Two elite (top ten national ranking) middle distance (1500 m) runners gave their informed written consent to participate in this study, which was conducted within the ethical guidelines of the Australian Institute of Sport. Data collection took place onsite at the Australian Institute of Sport on an outdoor synthetic rubber (Rekortan) 400 m athletic track. Subjects completed a 1500 m effort under simulated race conditions. Table 1 details subject performance in the 1500 m simulated race.

Equipment: Data were collected using two custom wearable instrumentation systems consisting of a microprocessor based data acquisition module [7], interfaced to micro-electromechanical system (MEMS) accelerometers and in-shoe load sensors [1]. The data acquisition module consisted of a battery-operated microprocessor, a 32 Megabyte multimedia memory card for data storage and a serial transceiver to facilitate communication with a host computer. The microprocessors had eight analog input channels of which three were used for measuring acceleration and four were used to measure in-shoe pressure. The microprocessors were programmed to synchronously sample each sensor at 500 Hz. These devices had a mass of 125 grams and could record continuously for more than 90 minutes.

The inertial sensors consisted of two dual-axis ±2 g (gravity) MEMS accelerometers (Analog Devices) mounted in a triaxial arrangement on a small circuit board. These devices were tested using a centrifuge to ±7 g. The triaxial accelerometer systems were semi-automatically calibrated using a six step inertial reference calibration technique developed by Lai et al. [8]. The data acquisition modules and the in-shoe sensor signal conditioning circuitry were incorporated into a semi-elastic belt, which was fastened around the subject's waist and the two triaxial accelerometer systems were placed side by side over the L3-L4 inter-vertebral space, approximating the subject's centre of mass. The three axes of the accelerometers were aligned in the vertical (V), anterior-posterior (AP) and medio-lateral (ML) axis of the subject's direction of progression.

Interfaced to the data acquisition module was a signal conditioning circuitry module for the in-shoe load sensors. The in-shoe load sensors were commercially available (paromed Vertriebs GmbH & Co. KG [9]) micro-electro-mechanical system (MEMS) piezoelectric micro-sensors embedded into silicone-filled hydrocells [2]. The discrete in-shoe sensors were deployed at a site approximating the heel, 1st metatarsal head (MTH), 3rd MTH and hallux of both the left and right foot. Hennig and Milani [5] identified these locations as representing the major load bearing structures of the human foot. Sensors were affixed with double-sided adhesive to the shoe liner of the subject's footwear. The in-shoe load sensors were connected to the signal conditioning circuitry module via a flexible wiring harness.

Data Processing: The chosen form of output was a graphical representation of the data, designed to give an indication of the shape and consistency of the recorded acceleration whilst comparing it to the insole pressure sensors. Initially a representative left/right pair of steps from each of six selected points of the 1500 m run were compared.

The acceleration data were converted from device based units to metres per second squared using a calibration step. To align the accelerometer vertically, the forward lean of the sensor was extracted using a low-pass filter (0.9 Hz) and from these data the orientation of the sensor with respect to gravity was derived. The difference between sensor vertical axis orientation and gravity was used to rotate the recorded data using a Euler rotation matrix (Fig. 1). This resulted in the vertical axis of the transformed data aligning with gravity. The transformed data were then both high pass filtered (0.9 Hz) and low pass filtered (25 Hz) using Hamming Window Finite Impulse Response (FIR) filters. The filtering step removed high frequency noise and the static orientation data.

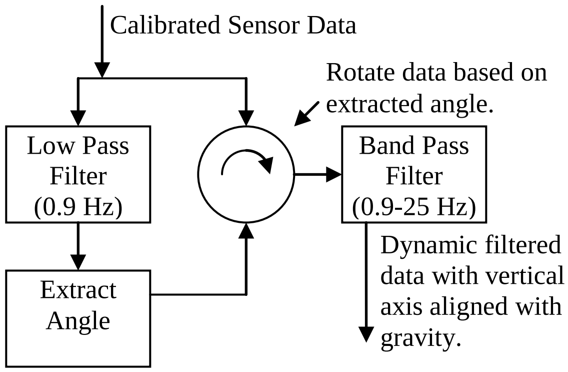

Fig. 1 Signal processing applied to accelerometer data

To generate a representative stride signal from selected race points, four successive strides were combined and averaged. This processing was performed automatically using an in-sole pressure threshold to identify and align the stride data. The same process can be performed using acceleration data alone. To allow the combining and comparison of strides of different frequencies, each individual stride was interpolated to give the same number of samples through the stride. The averaging process removed small inter-stride variations while maintaining the fundamental shape. The six selected race points occurred immediately before and after the completion of a split and included three samples of running on the curve and three samples of running on the straight. Due to the visual similarity of the data from the two triaxial accelerometers, only one set is used in the following analysis.

Results:

A notable result was the absence in the acceleration data of any significant curve running versus straight running identifying signature, in either the extracted orientation data or the dynamic running data. This is demonstrated in Figures 2 and 3 where the six traces for the race sample points cluster together making the data for each sensor appear as either a thick dark line or a tightly interwoven mix of lines. The signals for each acceleration axis and the in-sole sensors maintained an ongoing consistency across the sampled race points. The left hallux in-sole pressure increased during running on the curve (for both athletes).

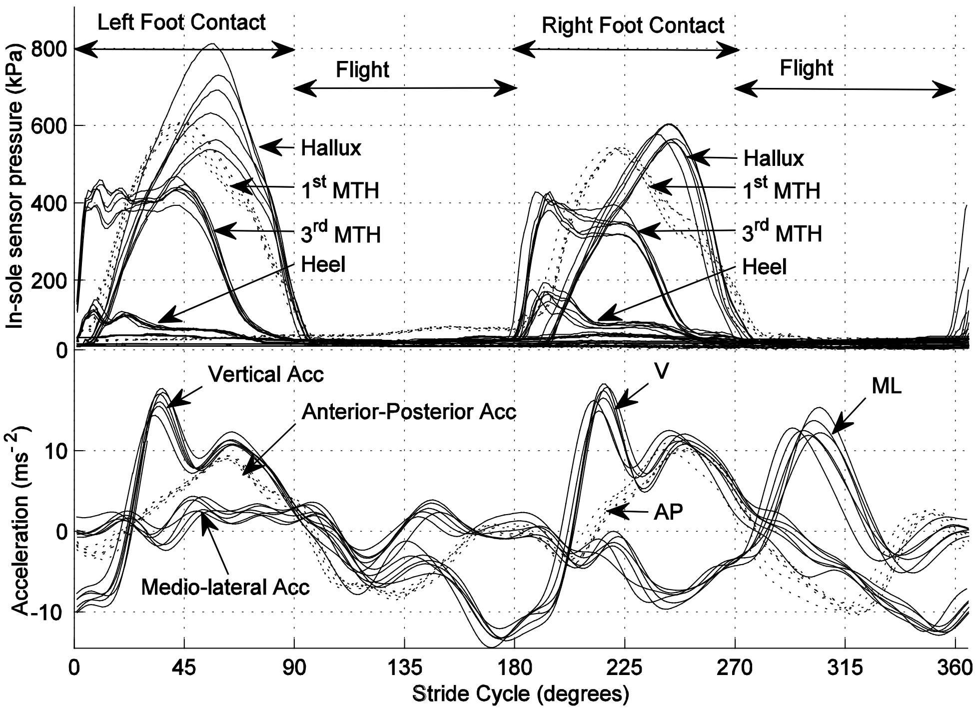

Fig. 2 Subject A, comparison of representative accelerometer and in-sole pressure data from six race points

Comparing in-sole pressure of subject A (Fig.2) with subject B (Fig.3) showed that subject A had a relatively small heel strike, with the majority of the pressure initially occuring on the 3rd MTH sensor and then moving to the 1st MTH sensor and finally to the hallux sensor. Subject B had a comparatively large heel pressure with the pressure then moving to the 3rd and 1st MTH sensors. Relative to the 1st MTH pressure the hallux pressure was quite small. This suggested that subject A landed with a flatter foot contact and then rolled forward to give the bulk of the final propulsion from a combination of the area around the 1st MTH and hallux. Subject B landed with the heel striking first and then obtained maximum pressure from the area of the 1st and 3rd MTHs (1st MTH area predominated).

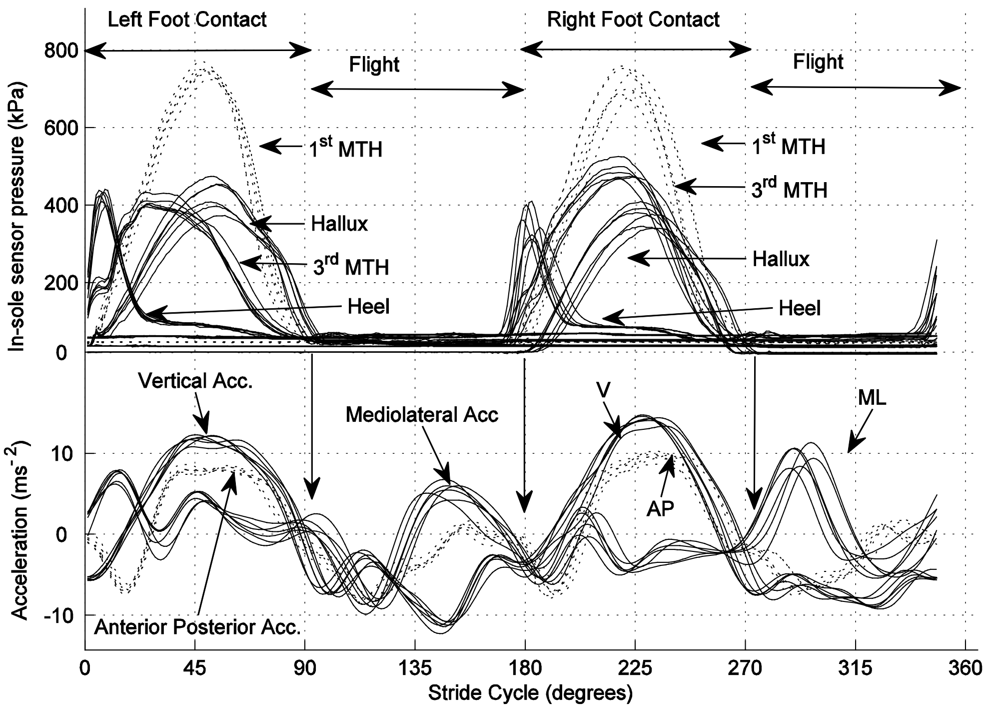

Fig. 3 Subject B, comparison of representative accelerometer and in-sole pressure data from six race points

When comparing the in-sole signal to the accelerometer signal, the anterior-posterior acceleration had a significant negative phase (braking) occurring at approximately the same time as the heel strike. This occurred for both athletes but was far more noticeable for subject B, who also had the much larger heel pressure. For both athletes the vertical acceleration went to zero at approximately the same time as foot contact ceased. Separate data collected from a subject on a treadmill showed the toe-off point moving as a function of speed, with the toe-off occurring later with respect to the acceleration data zero crossing as running speed decreased.

For these athletes, the orientation of the sensor extracted from the low-pass filter was reasonably stable for the duration of the race. For subject A, the rotation about the AP axis (sideways tilting) was less than 1.5 degrees and the forward lean of the sensor was less than 3 degrees. For subject B the corresponding values were less than 1 degree and around 11 degrees. For subject B these values made a noticeable difference in the relative size of the peak V and AP acceleration during contact when comparing the rotated acceleration (Fig.3) and the unrotated acceleration (Fig.4).

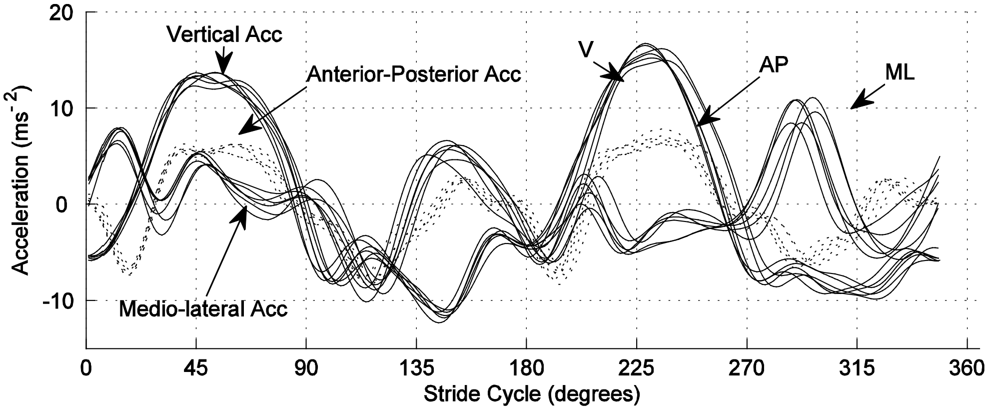

Fig. 4 Subject B, Un-rotated accelerometer data corresponding to Fig.3

Discussion:

The direct comparison between the in-sole pressure sensors and the accelerometer data indicates that the accelerometer data have significant markers that can be used in analysis of the athlete´s running style.

The approximate alignment of the anterior-posterior braking spike with the initial foot contact and the alignment of the vertical acceleration negative going zero crossing with the final foot contact gives an approximate measure of contact period. The size of the braking deceleration may be indicative of the size of the heel strike but this would require additional data collection from more subjects to confirm.

There may be other points of interest concealed in these data. For example, subject B appeared to supply the bulk of the force from an area centred around the 1st MTH and including the 3rd MTH and the hallux. Subject-B’s accelerometer data showed a large vertical acceleration and a lower forward acceleration. This compared with subject A where the in-sole pressure appeared to roll forward to the hallux. The acceleration for subject A showed an initial sharp spike* in the vertical acceleration (40 and 220 degrees into the stride cycle) and then the vertical and forward acceleration merged together (45-90 degrees and 225-270 degrees into the stride cycle) to give a continuous acceleration prior to toe-off of 45 degrees up and forward. In comparison, the combination of forward and upward acceleration for subject B gave a force trajectory of greater than 60 degrees upward. (* Other data collected by the authors indicated that the large spike was due to the transmittal of the initial foot impact up to the trunk mounted accelerometer sensor).

As subject A had a lower step frequency but ran a faster time (Fig.4 and Table 1), subject A also had a longer step length. It is possible that the ability to direct the trunk acceleration in a particular direction (45 degrees up and forward as opposed to 60 degrees up and forward) assisted in generating the longer step length. If in fact the interpretation that the hallux was significant in assisting to generate the apparent force vector, this would be consistent with Hennig's and Milani's results.

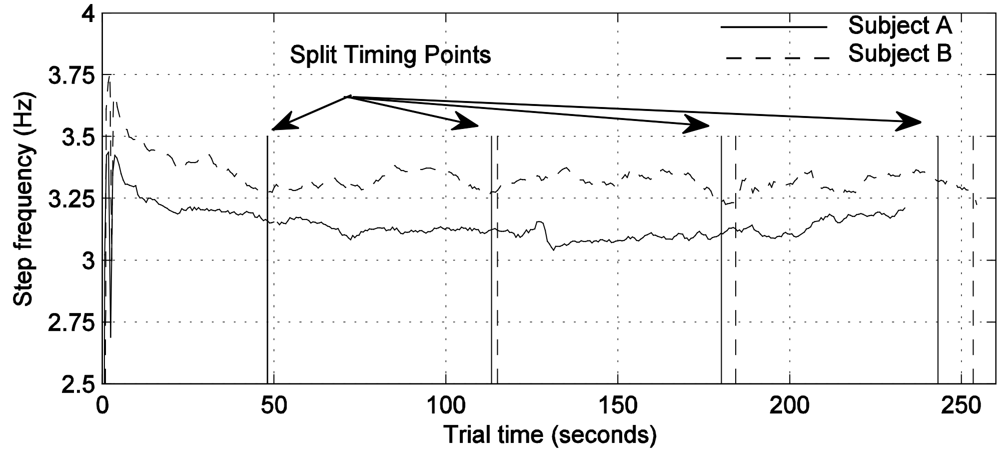

Fig. 5 Step frequency and split times for subjects over duration of the 1500 metres

Table 1: Performance of subjects during simulated 1500m race.

Simulated 1500m performance	Subject A	Subject B
1500m Race Time	243.20 s	253.32 s
Average 1500m Race Velocity	6.17 ms^{-1}	5.92 ms^{-1}
Average 1500m Step Frequency	3.14 Hz	3.32 Hz
Average 1500m Step Length	1.96 m	1.78 m

Conclusion:

Although this note only gives a brief qualitative analysis of the collected data, it appeared that the in-shoe pressure sensors allowed the framing of the triaxial centre-of-mass accelerometry such that the accelerometry could be used on its own to provide useful insight into the running technique of an athlete. The initial foot contact and final contact appeared to be discernable in the acceleration data, as did the effective application of contact forces.

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Conflict of Interest:

The authors declare that they have no conflict of interest.

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