THE USE OF A SINGLE INERTIAL SENSOR TO ESTIMATE GROUND REACTION FORCE DURING RUNNING: A PILOT STUDY

Jonathan White[1] Tim Exell[1], Joseph Moore[1] Cassie Wilson[2] and Gareth Irwin[3]

School of Sport, Health and Exercise Science, University of Portsmouth, Portsmouth, England[1] Department of Health, University of Bath, Bath, England[2] School of Sport and Health Sciences, Cardiff Metropolitan University, Cardiff, Wales[3]

Inertial sensors have the potential to measure and monitor loads during running in ecologically valid settings. The aim of this study was to investigate the suitability of the Delsys Trigno sensor to estimate ground reaction force (GRF) from resultant acceleration data in comparison to a force plate (FP). An inertial sensor was placed on the sacrum of three participants who undertook six runs at 3, 4 and 5 m/s over a FP. A strong correlation (r = 0.94) was observed for resultant step average force; with moderate coefficient of variation (CV) (9%) and root mean square error (RMSE) (10%) between the FP and force derived from acceleration (FAcc). Moderate correlation (r = 0.52), large CV (26%) and RMSE (36%) were observed for peak resultant GRF. Inertial sensors have potential to estimate average force, but with associated errors when compared with FP data (>10%).

KEY WORDS: accelerations, external loading, wearable sensors, field measurement.

INTRODUCTION: The assessment of bend running technique has received increased attention in recent literature (Alt et al., 2015; Churchill, Trewartha, & Salo, 2018; Judson et al., 2018). Force plates (FP) provide a well-established and effective gold-standard measure of kinetic data (Peterson Silveira et al., 2017; Robertson et al., 2004). Kinetic analyses of bend running however, are limited due to the difficulty in contacting a FP whilst running the curve. The use of a single accelerometer placed on the sacrum has been suggested to provide a valid estimate of ground reaction force (GRF) parameters during running and sit to stand tasks (Cerrito et al ., 2015; Gurchiek et al., 2017). These sensors have the potential to overcome the lack of portability and small capture areas associated with FPs. Therefore, enabling the assessment of sporting technique in ecologically valid settings**,** such as use on athletics tracks for bend running kinetic analyses.
Resultant GRF derived from the accelerometer has been suggested to be a more appropriate measure than vertical, anterior-posterior and medial-lateral GRFs when the orientation of the sensor is not known (Wundersitz et al., 2013), due to the fact that any deviation from the assumed vertical orientation of the device at foot contact has the potential to lead to cross-axis sensitivity of the accelerometer (Kaplan & Hegarty, 2006)**.** Additionally, Wundersitz et al., (2013) found the absolute error between a single inertial sensor and force plate to range from approximately 12% to 24% during running tasks. As well as resultant versus three-dimensional force estimation, researchers have investigated step averages and instantaneous values predicted by an inertial sensor. For example, step average showed strong correlations and small root mean square error (RMSE) (37.70 N to 77.05 N) a during sprint start task whilst instantaneous force RMSE was found to be < 370 N (Gurchiek et al., 2017). Nonetheless, each system has different on-board processing and sampling rates, thus, requiring scientific validation. The Delsys Trigno sensor measures both surface electromyography and tri-axial accelerations, therefore, providing potential to measure muscle activity and accelerations (giving a potential estimate of force) in ecologically valid environments, such as an athletics track. Thus, the aim of this validation study was to assess the suitability of the Delsys Trigno estimate of GRF derived from resultant accelerations compared to that of GRF data from a force platform during running.

METHODS: ***Procedure and Data Collection***
Following institutional ethical approval and informed consent; three males (age 24.33 ± 2.31 years; height 1.86.33 ± 5.51 m; mass 85.00 ± 12.49 kg; Mean ± SD) volunteered to take part. One Delsys Trigno Avanti (Delsys, USA) sensor (sampling at 150 Hz) was placed on the sacrum (between the posterior superior iliac spine), orientated with the y axis aligned with the longitudinal axis of the torso (Wundersitz et al., 2013). One force plate (Kistler 9281CA, Kistler, Switzerland; 1000 Hz) was mounted level with the ground in the laboratory and time synchronised with the Delsys system. Participants completed six trials running at 3, 4 and 5 m/s controlled by timing gates (TC Timing system, Brower, USA).
Data Analysis: Acceleration and GRF data were low pass filtered with a butterworth filter, using the optimal cut off frequency for each data set (Acceleration: 3.40 – 36.30 Hz; Force: 0.10 – 41.40 Hz) (Challis, 1999). Resultant force and acceleration were then calculated and resampled at the accelerometer sampling frequency (150 Hz). An estimate of ground reaction force was derived from the acceleration data (FAcc) using Newton's second law of motion: FAcc = m × Acc where FAcc is the force estimate derived from m (mass in kilograms) and Acc (acceleration in m/s^2) (Schmid, Hilfiker, & Radlinger, 2011). FP GRF and FAcc estimates were compared for the duration of foot contact. Foot contact was defined as the interval when the force plate measured vertical component was ≥ 10 N (Rabita et al., 2015). The mean force of the contact time interval was calculated for both GRF and FAcc data as well as peak resultant GRF.
Statistical Analysis: Normality tests were not undertaken due to a small sample size (< 10), thus non-parametric tests were used. The FAcc and FP GRF were compared using root mean square error (RMSE), Spearman's product moment correlation coefficient (r), and Bland-Altman 95% limits of agreement. Correlation coefficients were described in terms of strong (1.0 ≥ r ≥ 0.5), moderate (0.5 > r ≥ 0.3), and weak (r < 0.3) categories (Cohen, 1992). Coefficient of Variation (CV) was defined as small (CV < 5%), moderate (5% ≤ CV < 20%), and large (CV ≥ 20%) (Wundersitz et al., 2013). RMSE values were interpreted in line with previous inertial measurement unit research: with an acceptable accuracy being < 10 % of the mean of the reference system (Walgaard et al., 2016). All analysis were undertaken using custom code written in MATLAB (Mathworks, 2019b, USA).

RESULTS: For step average force (FP = 1,243.0 ± 854.0 N; FAcc = 1,559.0 ± 267.0 N) a strong correlation, moderate CV and unacceptable RMSE) were observed. For peak force values (FP = (2,153.0 ± 325.0 N; FAcc = 3,903.0 ± 854.0 N) with a moderate correlation, large CV and unacceptable RMSE were observed.

Table 1
Correlation coefficient, CV and RMSE for peak resultant force and average force during foot contact.

	Peak Force	Average Force
r	0.52	0.94
CV (%)	25.55	9.20
RMSE (N)	780	128

Comparative measure agreement for the average force during foot contact data can be seen in the Bland-Altman plot in Figure 1. The difference between the paired measurements is plotted on the y-axis and the average of the measures of the two methods on the x-axis, with results of this analysis indicating the differing absolute values of the measurement derived from the force plate (FP) and Delsys accelerometer (FAcc).

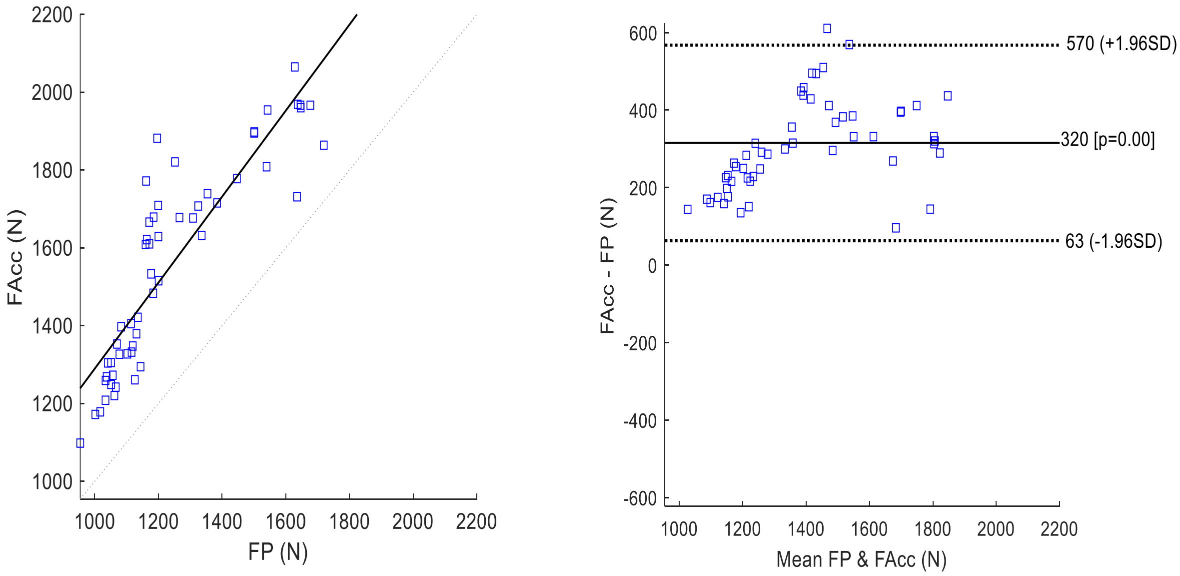

Figure 1: (Left) Scatter diagram showing GRF from FP and derived from accelerometer (FAcc) and the line of identity (dotted line) (Right) Bland-Altman plot showing the systematic (solid line) and random (dotted line) bias in the accelerometers estimate of Force.

DISCUSSION: The aim of this study was to assess the suitability of the Delsys Trigno to estimate aspects of GRF (step-average and peak resultant) derived from resultant accelerations compared to that of GRF data from a force platform during running. The results showed a strong correlation (r = 0.94) between the step average force between a force plate and an estimate of force derived from an accelerometer placed on the sacrum. A moderate CV (9.20 %) and marginally not acceptable RMSE 10.31 % (acceptable being defined as < 10 %) demonstrate that, while a strong relationship exists between the two measurement systems, the degree of accuracy may limit the current application of this method in research. Furthermore, peak FAcc showed a moderate correlation (r = 0.52), large CV (25.55 %) and unacceptable RMSE (36.22 %). Nonetheless, similar to previous research, these results showed a strong correlation for the estimation of average resultant force during foot contact (Gurchiek et al., 2017). The authors suggested the proposed method may be appropriate in applications where step-average values are of importance, such as the assessment of step-time asymmetries (Beck, Azua, & Grabowski, 2018). One possible cause for the discrepancy between FP and FAcc values is the relatively low sampling frequency of the Delsys Trigno accelerometer (150 Hz). Previous research has recommended a minimum of 500 Hz for the accurate assessment of kinetic variables during running (Mitschke, Zaumseil, & Milani, 2017). Additional potential causes of error include inaccuracies in terms of impact attenuation, the effects of running shoes and or sensor placement. Previous research has suggested an acceptable difference of < 10 % between the proposed method and the reference system (Walgaard et al., 2016). Nonetheless, this threshold may not be appropriate to detect meaningful differences in kinetics during bend running. Despite this, if the error associated is acknowledged, the method proposed using the Delsys Trigno system has the potential for use where force plates are not feasible, such as for monitoring load throughout indoor athletic sprint events (200 – 400 m).

CONCLUSION: The use of a single accelerometer placed on the sacrum to estimate resultant step-average force produced a strong correlation (r = 0.94) to that of a force plate. However, FAcc does not provide an acceptable level of accuracy when estimating peak ground reaction forces. Furthermore, the authors acknowledge the limitations associated with the small sample size of this study. Thus, coaches, researchers and practitioners should exercise caution when implementing the use of accelerometers into their practice to estimate kinetic parameters during linear running. Further research is required to improve the accuracy of this ground reaction force estimation method and to validate its use at greater speeds with a more appropriate sample size. Additionally, research should investigate three-dimensional force parameters to examine the usability of accelerometers for kinetic analyses assessment of bend running.

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