The relationship between inertial measurement unit derived 'force signatures' and ground reaction forces during cricket pace bowling.

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Abstract

This study assessed the reliability and validity of segment measured accelerations in comparison to front foot contact (FFC) ground reaction force (GRF) during the delivery stride for cricket pace bowlers. Eleven recreational bowlers completed a 30-delivery bowling spell. Trunk and tibia-mounted inertial measurement units (IMUs) were used to measure accelerations, converted to force, for comparisons to force plate GRF discrete measures. These measures included peak force, impulse, and the continuous force-time curve in the vertical and braking (horizontal) planes. Reliability and validity was determined by intra-class correlation coefficients (ICC), coefficient of variation (CV), Bland-Altman plots, paired sample t-tests, Pearson's correlation, and one-dimensional (1D) statistical parametrical mapping (SPM). All ICC (0.90-0.98) and CV (4.23-7.41%) were acceptable, except for tibia-mounted IMU braking peak force (CV=12.44%) and impulse (CV=18.17%), and trunk vertical impulse (CV=17.93%). Bland-Altman plots revealed wide limits of agreement between discrete IMU force signatures and force plate GRF. The 1D SPM outlined numerous significant ($p<0.01$) differences between trunk and tibia located IMU derived measures and force plate GRF traces in vertical and braking (horizontal) planes. The trunk and tibia-mounted IMUs appeared to not represent the GRF experienced during pace bowling FFC when compared to a gold-standard force plate.

Keywords: field based testing, loading, one-dimensional statistical parametrical mapping, reliability, validity.

Word Count: 197 (abstract)

Introduction

Cricket is a field-based, bat-and-ball game, played between two teams of 11 players. Within a cricket team, players have particular roles they perform (i.e. batting, bowling, and fielding), which dictates what the players' primary responsibilities are during a game. A pace bowler's primary goal is to dismiss the batsmen for as few runs as possible. One strategy pace bowlers adopt to achieve this goal is to decrease the decision-making and stroke execution time of the opposing batsman, via maximising ball release velocity (BRV). To generate a high BRV, pace bowlers complete a run-up to the crease before an explosive leap into the delivery stride. The delivery stride comprises high vertical and braking ground reaction forces (GRFs) experienced at rear and front foot contact (FFC) (Hurrion, Dyson and Hale, 2000). This occurs while the upper-body undergoes rapid lateral trunk flexion and hyperextension into ball release (Bartlett, Stockill, Elliott and Burnett, 1996; Elliott, 2000; Glazier, Paradisis and Cooper, 2000; Portus, Mason, Elliott, Pfitzner and Done, 2004). Research conducted on pace bowling has suggested that in elite male pace bowlers, higher peak vertical and braking forces, and braking impulse during FFC are associated with an increased BRV (King, Worthington and Ranson, 2016; Portus et al., 2004). However, it is important to note that the majority of research literature regarding BRV among pace bowlers has been conducted within the laboratory setting, which may influence the ecological validity of these findings.

The analysis of pace bowling in the laboratory has typically been undertaken with force plate, opto-reflective and video based systems (Ferdinands, Kersting and Marshall, 2009; King et al., 2016; Worthington, King and Ranson, 2013b). However, as laboratory-based testing may not appropriately replicate match intensity, performance or technique, there is a need for field-based assessment of factors associated with pace bowling performance (Wixted, Billing and James, 2010; Zheng, Liu, Inoue, Shibata and Liu, 2008). The recent increase in use of microsensors, which contain tri-axial accelerometers, gyroscopes and magnetometers, may represent an alternative to current laboratory-based methods for the assessment of GRFs during pace bowling, and the resulting effects on performance within match conditions.

Accelerometers housed within global positioning satellite (GPS) units and microsensors have previously been shown to accurately detect bowling events, such as back foot and FFC in training (Rowlands, James and Thiel, 2009), bowling counts in training and competition (McNamara, Gabbett, Chapman, Naughton and Farhart, 2015a), and PlayerLoad across a 12-over bowling spell (McNamara, Gabbett, Chapman, Naughton and Farhart, 2015b). A large positive ($r = 0.64$) relationship, as determined by a polynomial regression, has also been shown between resultant acceleration (resultant acceleration = $[x^2 + y^2 + z^2]^{0.5}$) and BRV among elite pace bowlers (McNamara, Gabbett and Naughton, 2017). This may be beneficial in the estimation of bowling loads, but this does not provide specific information regarding the actual external loads or GRFs experienced during each delivery as a more direct measure of load experienced. The use of accelerometers in the expression of GRFs has been undertaken in other sporting movements and activities of daily living (Elvin, Elvin and Arnoczky, 2007; Meyer et al., 2015). Significant correlations (average $r = 0.812$; $p < 0.01$) have been found between peak tibial acceleration and GRF during a countermovement jump in recreational male athletes (Elvin et al., 2007). In contrast, it has also been reported that accelerometers positioned on the upper trunk overestimate the vertical and resultant GRFs experienced during running, change of direction, landing and jumping tasks (Tran, Netto, Aisbett and Gastin, 2010; Wundersitz, Netto, Aisbett and Gastin, 2013). It is clear that the measurement of GRFs via microsensors requires greater investigation, as the location of the mounted microsensor can vastly influence the perceived load and subsequent GRF prediction

(Lundgren et al., 2016). As such, the relationship between trunk or tibial accelerations from accelerometers and GRF during FFC of the delivery stride in pace bowlers is largely unexplored, and this could provide pertinent field-based information regarding performance.

Several researchers have suggested that the amount or pattern of work performed during pace bowling may be a risk factor for injury (Dennis, Farhart, Goumas, & Orchard, 2003; Orchard et al., 2015; Portus et al., 2000). However, it is critical that research first evaluate the validity and reliability of technology proposing to quantify the load which can be worn during match-play or training. Specifically, there is a need to determine whether GRF measures derived from acceleration data measured by microsensors or more specifically inertial measurement units (IMUs) can be used with confidence in field-based settings for pace bowlers (Rowlands, James and Thiel, 2009). This could then lead to the ability to quantify the GRF experienced during a match, if the IMUs demonstrate acceptable reliability and validity. Consequently, this research determined the reliability and validity of accelerometer data, biomechanically expressed as GRF, collected from trunk and tibia mounted IMUs when compared to the criterion measure of a force plate, during FFC of the delivery stride in pace bowlers. It was hypothesised that the accelerometer data would be a reliable and valid representation of GRF during FFC for pace bowlers.

Methods

Participants

A total of 11 recreationally-trained males (age = 26.8 ± 2.2 years; mass = 86.6 ± 9.9 kg; height = 1.85 ± 0.05 m), who were proficient in the movements of cricket pace bowling were recruited for this study. The sample size was determined by a power analysis ($\alpha = 0.05$, power = 0.95, effect size = 1.24, calculated sample size = 11) using the variance between vertical acceleration and GRF data during a 0.3 m drop landing task, collected via a hip mounted accelerometer and force plate, respectively (Meyer et al., 2015). Furthermore, the number of participants recruited for the investigation is similar to or exceeds that of previous studies which have assessed the reliability and validity of mircosensor mounted segment acceleration data as compared to GRF during dynamic movements (Elvin et al., 2007; McNamara et al., in press; McNamara et al., 2015; Meyer et al., 2015; Tran et al., 2010). Participants were recruited if they: were 18 years of age or older; were deemed proficient in the movements of pace bowling; that is, adopted a technique which correctly encompassed all four phases of pace bowling (i.e. run-up, pre-delivery stride, delivery stride and follow through) with an attempt to deliver the ball as fast as possible within the laws of the game (i.e. participants were required to bowl not throw the ball), as determined by the lead researcher; and did not have any existing medical conditions that would compromise participation in the study. The procedures used in this study were approved by Edith Cowan University Human Research Ethics Committee (Project Number: 11948). All participants received a clear explanation of the study, including the risks and benefits of participation. Written informed consent was obtained from the participants prior to testing.

Procedures

This study utilised a cross-sectional design which required participants to undertake a single testing session within a laboratory setting to determine the reliability and validity of accelerometers housed within IMUs in the assessment of FFC GRF measures for pace bowlers (Elvin et al., 2007; Meyer et al., 2015; Nedergaard et al., 2017; Tran et al., 2010; Wundersitz et al., 2013). Comparisons were made to the criterion measure of an in-ground force plate. Participants refrained from intensive exercise and any form of stimulant in the 24-h period prior to testing. Prior to data collection, the participant's age, height, and body mass was recorded. Height was measured barefoot using a stadiometer (Ecomed Trading, Seven Hills, Australia). Body mass was recorded using digital scales (Tanita Corporation, Tokyo, Japan). A standardised warm-up, consisting of jogging, dynamic stretching of the lower-limbs, and progressive speed runs, was used for all participants.

Testing required each participant to perform a five-over (30 delivery), bowling spell, where their front foot was required to plant upon one in-ground force platform (McNamara et al., 2015a). If the participant failed to land with their entire front foot on the in-ground force platform, the trial was disregarded, and re-bowled. The dimensions of the laboratory afforded each participant a maximum run-up length of 40 m and follow through distance of 20 m. Therefore, the laboratory dimensions allowed each bowler to use their normal full length run-up and follow through while bowling deliveries on the equivalent of a standard-sized cricket pitch (Figure 1). The average of all 30 trials was used for analysis for each participant (Nedergaard et al., 2017). A two-minute rest period, which is atypical of match play, was provided between each over, as well as a self-selected duration of active recovery as the participant walked back to the start of their run-up between each delivery. All bowlers used a red, four-piece kookaburra cricket ball (A.G. Thompson Pty. Ltd., Australia). Participants wore their own athletic shoes during testing.

INSERT FIGURE 1 ABOUT HERE

Participants were fitted with two wireless, time synchronised IMUs (MTw, XSENS Technology, Enschede, The Netherlands) weighing 27 grams, which contained a tri-axial accelerometer with a sample frequency of 75 Hz and an output range of ± 16 times gravity (g). In accordance with previous research (Wundersitz, Netto, Aisbett, & Gastin, 2013), the IMUs were calibrated by the manufacturer prior to commercial distribution and were not calibrated in this study. Acceleration data was collected using the accelerometers housed within the IMUs mounted on the trunk and tibia of the front foot, with respect to their delivery stride (Elvin et al., 2007; Tran et al., 2010; Wundersitz et al., 2013). The trunk mounted IMU was positioned on the dorsal part of the upper trunk between the scapula on the participant's skin via double sided tape, additional strapping tape was used to decrease movement artefact (Figure 2) (Nedergaard et al., 2017; Tran et al., 2010; Wundersitz et al., 2013). The IMU mounted on the tibia was positioned close to the knee in a manufacturer supplied click-in body strap (Figure 2) (Cloete and Scheffer, 2010). To ensure both IMUs were orientated in the same direction for all participants, the IMUs were physically marked with their orientation coordinate systems. The orientation coordinate system of each IMU outlined that the x-axis represented the vertical, the z-axis the braking (horizontal), and the y-axis the medial/lateral plane of motions. This did not align with the force plate reference frame (z-axis represented the vertical; y-axis represented the braking (horizontal); x-axis represented the medial/lateral plane of motions), however simple conversions were performed to allow for comparison between measures. Acceleration data in the vertical and braking (horizontal) planes were recorded and used to calculate a biomechanical representation of GRF, described as a force signature, during FFC of the delivery stride. The force signature was calculated via multiplying the acceleration values by the participant's body mass (Wundersitz et al., 2013). This estimation of loading is based upon Newton's second law of motion ($F_{whole\text{-}body} = m_{whole\text{-}body} \cdot a_{whole\text{-}body}$) and the assumption that body-worn accelerometers are an appropriate representation of whole-body acceleration (Nedergaard et al., 2017).

INSERT FIGURE 2 ABOUT HERE

To validate the force signature measurements derived from the IMUs, an in-ground tri-axial force plate (9287CA, Kistler Group, Winterthur, Switzerland), measuring 0.9 m by 0.6 m and sampling at 975 Hz, collected GRF data during FFC of the delivery stride. Flooring surface (Mondo S.p.A., Alba, Italy) of the laboratory and on top of the force platform was consistent. Both IMUs and the in-ground force plate were time synchronised through an analogue board which allowed the IMU recording software (MT Manager Version 4.2.1, XSENS Technology, Enschede, The Netherlands) to trigger data capture within the force plate software (Bioware Version 5.3.0.7, Kistler Group, Winterthur, Switzerland**)** via a voltage rising edge configuration.

Initially, inherent to the IMUs, a signal processing pipeline was performed upon the raw analog accelerometer signal which entailed a third order analog low-pass Bessel filter with a cut-off frequency of 120 Hz. Following this, to assist with the removal of random noise from the accelerometer data, a fourth order, zero lag, dual pass, Butterworth digital filter with a cut-off frequency of 10 Hz was applied to the exported x- and z-axis data during FFC (Wundersitz et al., 2013). This process was performed in a customised MATLAB R2015b (The MathWorks Inc, Massachusetts, USA) program which also generated the force signature values utilised for analysis. All FFC GRF measures were calculated within the force platform software (Bioware Version 5.3.0.7, Winterthur, Switzerland). Discrete variables were determined for the entire FFC, and include the following:

- Vertical peak – maximum force or force signature measured in the vertical direction.
- Braking peak – maximum force or force signature measured in the posterior direction.

- Vertical impulse – calculated as the area under the vertical force or force signature time curve.
- Braking impulse – calculated as the area under the anterior/posterior force or force signature time curve.

Vertical and braking peak and impulse measures were calculated for the force plate and tibia IMU, with only the vertical peak and impulse measured at the trunk IMU. The actions of the trunk (i.e. increased flexion and forward rotation) during FFC necessitate only investigating the vertical plane, as the accelerations in the braking (horizontal) plane are not reflective of the GRF experienced (King et al., 2016; Middleton, Mills, Elliott and Alderson, 2016; Worthington, King and Ranson, 2013a). The continuous force-time curve for the entire FFC was also assessed for both the GRF and force signature measures in the vertical and braking (horizontal) planes.

Statistical Analysis

Descriptive statistics (mean ± standard deviation [SD]) profiled each measured parameter. Several statistical approaches were used in this study. Normality of data was assessed by visual analysis of the Q-Q plot (Nimphius, McGuigan, Suchomel and Newton, 2016). A one-sample t-test was performed on the calculated difference between GRF and force signature discrete values, with comparisons made to zero. This was undertaken to determine whether a Bland-Altman plot was necessary to ascertain the limits of agreement between the discrete force signature and GRF measures during FFC of the delivery stride (Bakhshi, Mahoor and Davidson, 2011; Bergamini et al., 2013; Stamm, James and Thiel, 2013). A two-tailed paired samples t-test was used to determine any significant differences between the GRF and force signature discrete measures, with significance set at $p < 0.05$ (Tran et al., 2010; Wundersitz et al., 2013). Pearson's correlation analysis was also performed to examine the relationship between the criterion and IMU discrete measures. The strength of the correlation coefficient (*r*) was designated as previously recommended with an *r* value between 0 and 0.30 or 0 and -0.30 was considered small, 0.31 and 0.49 or -0.31 and -0.49 moderate; 0.50 and 0.69 or -0.50 and -0.69 large; 0.70 and 0.89 or -0.70 and -0.89 very large; and 0.90 and 1.00 or -0.90 and -1.00, near perfect for predicting relationships (Hopkins, 2009).

For the relative reliability analysis, intra-class correlation coefficients (ICC) were used to determine trial-to-trial variability of discrete measures. An ICC ≥0.70 was considered acceptable (Baumgartner and Chung, 2001; Hori et al., 2009). Absolute reliability of discrete measures was assessed by typical error of measurement (TEM) (Hopkins, 2000; Sheppard, Young, Doyle, Sheppard and Newton, 2006; Spencer, Fitzsimons, Dawson, Bishop and Goodman, 2006). The TEM was calculated through the formula: *TEM = Standard Deviation x √(1 – ICC).* The coefficient of variation (CV) was expressed as a percentage, which was calculated by the formula CV = 100 x *[(1 –[(test score – TEM) ÷ test score])* (Buchheit, Lefebvre, Laursen and Ahmaidi, 2011; Hopkins, 2000). A CV of less than 10% was set as the criterion for reliability (Cormack, Newton, McGuigan and Doyle, 2008; Standing and Maulder, 2017). These statistics were computed using the Statistics Package for Social Sciences Version 23.0 (IBM, Armonk, USA).

One-dimensional (1D) statistical parametric mapping (SPM) was used to evaluate if there were significant differences between the patterns and timing of force production as measured by the IMUs and force plate. Briefly, 1D SPM uses random field theory to objectively identify field regions which co-vary significantly with the experimental design (Pataky, Robinson and Vanrenterghem, 2013; Pataky, Vanrenterghem and Robinson, 2016). A two tailed paired sample t-tests were performed on the normalised time series data from the FFC to determine if a significant

($p < 0.05$) difference was present between the GRF and force signature measures. The 1D SPM analysis required four steps as outlined in previous research (De Ridder et al., 2013). All 1D SPM analyses were implemented in MATLAB Version R2015b (The MathWorks Inc, Massachusetts, USA) using the open source package located at http://www.spm1d.org/ "rft1d" (Pataky, 2016).

Results

The one-sample t-test results pertaining to the difference between GRF and discrete force measures compared to zero revealed significant ($p < 0.01$) differences for the vertical impulse measured at the trunk and tibia IMUs, as well as vertical peak force at the tibia IMU. Therefore, these measures demonstrated limited agreement, indicating the discrete force signatures did not represent the equivalent GRF measures. However, all other discrete measures (trunk IMU vertical peak force, and tibia IMU braking peak force and impulse) were not significantly different (p = 0.208-0.632). Figure 3 depicts the Bland-Altman plots of the trunk IMU vertical peak force, and tibia IMU braking peak force and impulse when compared to the equivalent criterion measure from the force plate. The wide limits of agreement indicated that there was great variability at the individual level, suggesting that both the trunk and tibia IMUs were not representative of vertical and braking GRF peaks and impulses during FFC of the delivery stride during pace bowling equally across participants. Further to this, a significant ($p < 0.01$) difference, as determined by the two-tailed paired sample t-test, was present between the tibia IMU vertical peak and impulse, and trunk IMU vertical impulse when compared to the equivalent GRF measures. No other significant differences were present between IMU and force plate data (p = 0.208-0.632) (Table 1).

INSERT FIGURE 3 ABOUT HERE

A very large significant ($p < 0.01$) correlation was present between the tibia IMU vertical peak ($r = 0.832$) and impulse ($r = 0.865$) and force plate criterion measures. All other correlations demonstrated non-significant ($p = 0.581$-0.657) small relationships ($r = -0.151$-0.187) between the IMU and force plate discrete measures. Table 1 displays the descriptive data, ICC, TEM, and CV for each assessed variable across the IMU and force plate discrete measures. All ICCs were deemed acceptable. However, trunk IMU vertical impulse, tibia braking peak and impulse measures all exceeded the 10% CV acceptable threshold while all other variables demonstrated acceptable CVs.

INSERT TABLE 1 ABOUT HERE

Figure 4 depicts the results from the 1D SPM analysis. A significant ($p < 0.01$) difference was present between the vertical GRF and trunk IMU force signature curves during 0-24%, and 48-93% of FFC time. The tibia IMU force signature curve in the vertical plane reported significant differences at 0-10% ($p < 0.01$) and 34% ($p = 0.019$) of FFC time, when compared to the equivalent GRF curve. A significant ($p < 0.01$) difference was also established between the tibia IMU force signatures in the braking (horizontal) plane during 27-31%, 41-51%, and 65-89%, and the GRF curve.

*** INSERT FIGURE 4 ABOUT HERE***

Discussion and Implications

This is the first study to assess the reliability and validity of IMUs in the determination of GRFs, as a means of potential field-based performance assessments for cricket pace bowlers. Contrary to the studies' hypothesis, the results suggested that force signatures calculated via trunk and tibia mounted IMUs did not accurately represent GRFs measured via a force plate in the vertical or braking (horizontal) planes. This may partially be attributed to the complex sequencing of multi-segment motions during pace bowling (Ferdinands et al., 2009; Worthington et al., 2013b; Zhang, Unka and Liu, 2011), which limits the ability of a simple relationship between a segment force signature and GRF to be present. The use of segment force signatures in the vertical plane could provide useful new data about pace bowling performance within the field setting, although further research is needed to assess this hypothesis.

The discrete vertical peak force results calculated from the trunk mounted IMU demonstrated acceptable levels of absolute (ICC = 0.97) and relative (CV = 7.41%) reliability, and no significant difference to GRF variables. The acceptable relative and absolute reliability may indicate that trunk acceleration may provide useful information regarding load received during pace bowling. However, additional research is required to determine the usefulness of segment acceleration data with respect to the appropriateness of the trunk measured accelerations as an isolated versus global load measure within the field setting. This is especially true, due to the poor agreement shown between the trunk mounted IMU force signature and GRF traces as well as the poor agreement between trunk IMU discrete peak braking force and impulse to GRF equivalents.

Specifically, the Bland-Altman plot revealed a wide limit of agreement for peak vertical measures calculated via the trunk mounted IMU, and the 1D SPM analysis illustrated that only 25-47% and 94-100% of the FFC phase had similarity between vertical force signature and GRF trajectories. Previous research has demonstrated similar findings, with small-to-moderate correlations (r = -0.26-0.39) between vertical peak GRFs quantified by a force plate, and force signature measures determined by a trunk mounted accelerometer housed within a microsensor tracking device during running and change of direction tasks (Wundersitz et al., 2013). The movements of the trunk through all three planes of motion during FFC (i.e. lateral flexion, rotation and flexion) (Bartlett et al., 1996; Elliott, 2000; Glazier et al., 2000; Portus et al., 2004) may have contributed to the study findings. During the pace bowling action, a bowler rapidly rotates their trunk towards the opposing batsmen, from initial FFC to ball release which greatly increase the angular rotation of the trunk (Ferdinands et al., 2009; Ferdinands, Kersting, Marshall and Stuelcken, 2010). High angular rotation of a segment has been associated with errors in acceleration data, due to the crosstalk between sensing axes (Kavanagh and Menz, 2008). Clearly, future research is required to determine the usefulness of accelerations measured at the trunk to pace bowling performance, as the current study indicated acceptable levels of reliability, however a poor level of agreement with GRFs. Such findings are not a disqualification of the use of trunk measured variables but merely highlight the measured loads are providing different information than that derived by measuring GRF that must be further evaluated.

The tibia mounted IMU force signature data in the vertical plane was not a good indicator of vertical GRF during FFC for pace bowlers, as it significantly over-estimated peak and impulse values. In addition, the 1D SPM analysis demonstrated that the initial loading (0-10 % of the FFC phase) of the force signature trajectory was significantly different to the GRF trajectory. This finding is contrary to previous research which outlined that a tibia mounted accelerometer demonstrated the strongest relationship (R^2 = 0.45) to loading rate, as determined by a force plate, when compared to trunk and hip mounted accelerometers during a submaximal linear run completed at between 2-5 m/s (Nedergaard et al., 2017). Despite this only explaining 45% of the variance, the lack of agreement within the results of the current study and to that of previous research (Nedergaard et al., 2017) could also be a consequence of the front foot ground contact positon relative to the centre of mass of the pace bowler. Pace bowlers will typically have a FFC in advance of their centre of mass, leading to a more acute tibia angle with respect to the horizontal. This could then influence the vertical component of the force signature in relation to the actual GRF generated by the total mass of the bowler (Worthington et al., 2013a). There was an acceptable measurement of error, as well as a positive correlation between force signature and GRF discrete measures. This may indicate measures from an IMU located at the tibia could provide useful information about segment vertical impact forces experienced during FFC within the field setting. However, this measurement will be distinct from the actual GRF of the pace bowler's total mass, and more research is required to determine whether the measurement of segment vertical impact force via an IMU provides useful pace bowling information.

The tibia mounted IMU also appeared to not be representative of GRF measured via a force plate in the braking (horizontal) plane. The braking discrete measures demonstrated a large degree of variance which led to wide limits of agreement presented within the Bland-Altman plot analyses. The 1D SPM analysis also revealed significant differences between the force signature and GRF trajectories in the braking (horizontal) plane during 27-31 %, 41-51 %, and 65-89 % of the FFC phase. These results suggested that the movements of a single segment during the pace bowling action may not allow for an accurate representation of the overall braking GRFs experienced as measured by a force plate. The reliability and validity of IMUs with respect to GRF may be dependent upon the movement task (Nedergaard et al., 2017). As pace bowling is a complex multi-segment action, the relationship between segmental measures (e.g. vertical tibia) to whole-body GRF measures will vary vastly between individuals dependent on factors such as mass distribution and segmental timing.

There are certain limitations of this study that must be considered. The use of recreational pace bowlers led to a substantial reduction (~2.64 N/body weight [BW]) in the magnitude of peak vertical GRFs reported when compared to elite and high performance (4.5-6.72 N/BW) pace bowlers (King et al., 2016; Middleton et al., 2016). Nonetheless, the use of amateur and recreational athletes is common among validity and reliability studies and typically allows for a more robust analysis due to greater within-participant variability (Nedergaard et al., 2017; Tran et al., 2010; Wundersitz et al., 2013). This may limit how these results can be applied to elite populations, thus future research should investigate the accuracy of IMUs in the calculation of loading among elite pace bowlers. In addition, the IMUs utilised within this study had a low sample frequency (75 Hz). However, the sample frequency used within this study is similar to that of other commercially based accelerometers (100 Hz). This is of importance, as 100 Hz accelerometers are widely used within field-based sports, including cricket (McNamara et al., in press; McNamara et al., 2015). The absence of a preceding calibration of the IMU prior to data collection may have influenced the quality of the data collected (Nez, Fradet, Laguillaumie, Monnet, & Lacouture, 2016). However, the procedures used in this study are in accordance with previous research (Wundersitz, Netto, Aisbett, & Gastin, 2013), and it may be suggested would be representative of practices in the field setting. As calibration of IMUs can require specialised lab-based equipment and complex calculations (Nez et al., 2016). Nonetheless, future research should investigate the influence of IMU calibration procedures upon their ability to accurately determine GRF during FFC for cricket pace bowlers. The degree of movement artefact present as a result of the IMU mounting on the trunk and tibia may have influenced the results. Nevertheless, all appropriate measures were taken to limit the degree of movement artefact, which was in accordance with previous research (Cloete and Scheffer, 2010; Kavanagh and Menz, 2008).

Conclusion

The results from this study suggested that the assumption of a simple relationship where segmental acceleration measured by body-mounted IMUs will provide a reliable and valid representation of the GRFs experienced during FFC of the pace bowling action may not be appropriate. There was a lack of agreement between force signature and GRF discrete measures, and the 1D SPM analysis demonstrated that large percentages of the FFC phase in which the two trajectories significantly differed, for both trunk and tibia mounted IMUs. It would seem apparent that the study results suggest that segmental acceleration is not an appropriate representation of whole body acceleration, a key principle to the suggested theory (Nedergaard et al., 2017), for cricket pace bowlers. Alternatively, segment acceleration may provide new information which is related to pace bowling performance which can be collected within the field. However, future research is needed to determine this.

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References

Bakhshi, S., Mahoor, M. H. & Davidson, B. S. (2011). *Development of a body joint angle measurement system using IMU sensors*. 33rd Annual International Conference of the IEEE EMBS (p. 6923-6926). Boston, Massachusetts USA.

Bartlett, R. M., Stockill, N. P., Elliott, B. C. & Burnett, A. F. (1996). The biomechanics of fast bowling in men's cricket: A review. *Journal of Sports Sciences, 14*(5), 403-424.

Baumgartner, T. A. & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science, 5*(3), 179-188.

Bergamini, E., Guillon, P., Camomilla, V., Pillet, H., Skalli, W. & Cappazzo, A. (2013). Trunk inclination estimate during the sprint start using an inertial measurement unit: A validation study. *Journal of Applied Biomechanics, 29,* 622-627.

Buchheit, M., Lefebvre, B., Laursen, P. B. & Ahmaidi, S. (2011). Reliability, usefulness, and validity of the 30-15 Intermittent Ice Test in young elite ice hockey players. *Journal of Strength and Conditioning Research*, *25*(5), 1457-1464.

Cloete, T. & Scheffer, C. (2010). *Repeatability of an off-the-shelf, full body inertial motion capture system during clinical gait analysis*. 32nd Annual International Conference of the IEEE EMBS (p. 5125-5128). Buenos Aires, Argentina.

Cormack, S. J., Newton, R. U., McGuigan, M. R. & Doyle, T. L. A. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology & Performance, 3*(2), 131-144.

Dennis, R., Farhart, R., Goumas, C., & Orchard, J. (2003). Bowling workload and the risk of injury in elite cricket fast bowlers. *Journal of Science and Medicine in Sport, 6*(3), 359-367.

De Ridder, R., Willems, T., Vanrenterghem, J., Robinson, M., Pataky, T. & Roosen, P. (2013). Gait kinematics of subjects with ankle instability using a multisegmented foot model. *Medicine and Science in Sports and Exercise, 45*(11), 2129-2136.

Elliott, B. (2000). Back injuries and the fast bowler in cricket. *Journal of Sports Sciences, 18*(12), 983-991.

Elvin, N. G., Elvin, A. A. & Arnoczky, S. P. (2007). Correlation between ground reaction force and tibial acceleration in vertical jumping. *Journal of Applied Biomechanics, 23*(3), 180-189.

Ferdinands, R., Kersting, U. & Marshall, R. N. (2009). Three-dimensional lumbar segment kinetics of fast bowling in cricket. *Journal of Biomechanics, 42,* 1616-1621.

Ferdinands, R., Kersting, U., Marshall, R. N. & Stuelcken, M. C. (2010). Distribution of modern cricket bowling actions in New Zealand. *European Journal of Applied Physiology, 10*(3), 179-190.

Glazier, P. S., Paradisis, G. P. & Cooper, S.-M. (2000). Anthropometric and kinematic influences on release speed in men's fast-medium bowling. *Journal of Sports Sciences, 18*(12), 1013-1021.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

Hopkins, W. G. (2009). *A scale of magnitude for effect statistics*. Retrieved from www.sportsci.org/resource/stats/index.html.

Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J. & Nosaka, K. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research, 23*(3), 874-882.

Hurrion, P. D., Dyson, R. & Hale, T. (2000). Simultaneous measurement of back and front foot ground reaction forces during the same delivery stride of the fast-medium bowler. *Journal of Sports Sciences, 18*, 993-997.

Kavanagh, J. J. & Menz, H. B. (2008). Accelerometry: A technique for quantifying movement patterns during walking. *Gait & Posture, 28*(1), 1-15.

King, M. A., Worthington, P. J. & Ranson, C. A. (2016). Does maximising ball speed in cricket fast bowling necessitate higher ground reaction forces? *Journal of Sports Sciences, 34*(8), 707-712.

Lundgren, L. E., Tran, T. T., Nimphius, S., Raymond, E., Secomb, J. L., Farley, O. R. L., Newton, R. U. & Sheppard, J. M. (2016). Comparison of impact forces, accelerations and ankle range of motion in surfing-related landing tasks. *Journal of Sports Sciences, 34*(11), 1051-1057.

McNamara, D., Gabbett, T., Chapman, P., Naughton, G. & Farhart, P. (2015a). The validity of microsensors to automatically detect bowling events and counts in cricket fast bowlers. *International Journal of Sports Physiology & Performance*, *10*(1), 71-75.

McNamara, D., Gabbett, T., Chapman, P., Naughton, G. & Farhart, P. (2015b). Variability of PlayerLoad, bowling velocity, and performance execution in fast bowlers across repeated bowling spells. *International Journal of Sports Physiology & Performance, 10*(8), 1009-1014.

McNamara, D., Gabbett, T. & Naughton, G. (2017). Assessment of workload and its effects on performance and injury in elite cricket fast bowlers. *Sports Medicine, 47*(3), 503-515.

Meyer, U., Ernst, D., Schott, S., Riera, C., Hattendorf, J., Romkes, J., Granacher, U., Göpfert, B. & Kriemler, S. (2015). Validation of two accelerometers to determine mechanical loading of physical activities in children. *Journal of Sports Sciences, 33*(16), 1702-1709.

Middleton, K. J., Mills, P. M., Elliott, B. C. & Alderson, J. A. (2016). The association between lower limb biomechanics and ball release speed in cricket fast bowlers: a comparison of high-performance and amateur competitors. *Sports Biomechanics, 15*(3), 357-369.

Nedergaard, N. J., Robinson, M. A., Eusterwiemann, E., Drust, B., Lisboa, P. J. & Vanrenterghem, J. (2017). The relationship between whole-body external loading and body-worn accelerometry during team-sport movements. *International Journal of Sports Physiology & Performance, 12*(1), 18-26.

Nez, A., Fradet, L., Laguillaumie, P., Monnet, T., & Lacouture, P. (2016). Comparison of calibration methods for accelerometers used in human motion analysis. *Medical Engineering and Physics, 38*(11), 1289-1299.

Nimphius, S., McGuigan, M. R., Suchomel, T. J. & Newton, R. U. (2016). Variability of a “force signature” during windmill softball pitching and relationship between discrete force variables and pitch velocity. *Human Movement Science, 47*, 151-158.

Orchard, J. W., Blanch, P., Paoloni, J., Kountouris, A., Sims, K., Orchard, J. J., & Brukner, P. (2015). Cricket fast bowling workload patterns as risk factors for tendon, muscle, bone and joint injuries. *British Journal of Sports Medicine*, *49*(16), 1064-1068.

Pataky, T. (2016). rft1d: Smooth one-dimensional random field upcrossing probabilities in Python. *Journal of Statistical Software, 71*(7), 1-22.

Pataky, T., Robinson, M. & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics, 46*(14), 2394-2401.

Pataky, T., Vanrenterghem, J. & Robinson, M. (2016). The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and EMG trajectories. *Journal of Biomechanics*, *49*(9), 1468-1476.

Portus, M. R., Mason, B. R., Elliott, B. C., Pfitzner, M. C. & Done, R. P. (2004). Technique factors related to ball release speed and trunk injuries in high performance cricket fast bowlers. *Sports Biomechanics*, *3*(2), 263-283.

Rowlands, D., James, D. A. & Thiel, D. V. (2009). Bowler analysis in cricket using centre of mass inertial monitoring. *Sports Technology, 2*(1), 39-42.

Sheppard, J. M., Young, W. B., Doyle, T. L., Sheppard, T. A. & Newton, R. U. (2006). An evaluation of a new test of reactive agility and its relationship to sprint speed and change of direction speed. *Journal of Science and Medicine in Sport, 9*(4), 342-349.

Spencer, M., Fitzsimons, M., Dawson, B., Bishop, D. & Goodman, C. (2006). Reliability of a repeated-sprint test for field-hockey. *Journal of Science and Medicine in Sport, 9*(1-2), 181-184.

Stamm, A., James, D. A. & Thiel, D. V. (2013). Velocity profiling using inertial sensors for freestyle swimming. *Sports Engineering*, *16*, 1-11.

Standing, R. J. & Maulder, P. S. (2017). The biomechanics of standing start and initial acceleration: reliability of the key determining kinematics. *Journal of Sports Science & Medicine, 16*(1), 154-162.

Tran, J., Netto, K., Aisbett, B., & Gastin, P. (2010). *Validation of accelerometer data for measuring impacts during jumping and landing tasks*. 28th International Symposium on Biomechanics in Sports (p. 1-4). Marquette, Michigan.

Weerakkody, N. & Allen, T. (2017). The effects of fast bowling fatigue and adhesive taping on shoulder joint position sense in amateur cricket players in Victoria, Australia. *Journal of Sports Sciences*, *35*(19), 1954-1962.

Wixted, A. J., Billing, D. C. & James, D. A. (2010). Validation of trunk mounted inertial sensors for analysing running biomechanics under field conditions, using synchronously collected foot data. *Sports Engineering, 12*, 207-212.

Worthington, P. J., King, M. A. & Ranson, C. A. (2013a). The influence of cricket fast bowlers' front leg technique on peak ground reaction forces. *Journal of Sports Sciences, 31*(4), 434-441.

Worthington, P. J., King, M. A. & Ranson, C. A. (2013b). Relationship between fast bowling technique and ball release speed in cricket. *Journal of Applied Biomechanics*, *29*, 78-84.

Wundersitz, D. W. T., Netto, K. J., Aisbett, B. & Gastin, P. B. (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*(4), 403-412.

Zhang, Y., Unka, J. & Liu, G. (2011). Contribution of joint rotations to ball release speed during cricket bowling: A three-dimensional kinematic analysis. *Journal of Sports Sciences*, *29*(12), 1293-1300.

Zheng, R. T., Liu, T., Inoue, Y., Shibata, K. & Liu, K. (2008). Kinetics analysis of ankle, knee and hip joints using a wearable sensor system. *Journal of Biomechanical Science and Engineering*, *3*, 343-355.

Table 1: The ground reaction force measured by a force plate and front foot tibia inertial measurement unit (IMU) force signatures for vertical and braking peaks and impulses, and the trunk IMU vertical peak force signature and impulse measurements during front foot contact of the delivery stride of the pace bowling action in recreational bowlers (n = 11).

Variable	Force Plate	Trunk IMU	Tibia IMU
Vertical Peak			
Force (N)	2228.43 ± 837.99	2403.47 ± 995.38	4295.66 ± 1393.41[a]
ICC	0.98	0.97	0.98
TEM	129.82	178.06	181.68
CV (%)	5.83	7.41	4.23
Vertical Impulse			
Impulse (N · s)	448.28 ± 129.27	210.73 ± 178.15[a]	620.73 ± 177.00[a]
ICC	0.99	0.96	0.97
TEM	10.01	37.79	30.14
CV (%)	2.23	17.93	4.86
Braking Peak			
Force (N)	-1291.44 ± 703.04		-1861.63 ± 1115.90
ICC	0.99		0.96
TEM	31.44		231.40
CV (%)	2.43		12.43
Braking Impulse			
Impulse (N · s)	-96.21 ± 41.95		-106.57 ± 59.77

ICC	0.99	0.90
TEM	1.33	19.37
CV (%)	1.38	18.17

[a]Significantly ($p < 0.05$) different from the force plate criterion measure. N = Newtons; ICC = intra-class correlation coefficient; TEM = typical error of measurement; CV = coefficient of variation; N · s = Newtons per second.

Figure 1: A standard-sized cricket pitch.

Figure 2: The position of the inertial measurement unit on both the dorsal part of the upper trunk (A) and tibia (B).

Figure 3: The Bland-Altman plots of the difference (force plate – accelerometer) versus mean values measured by the inertial measurement unit (IMU) and force plate with 95% limits of agreement. (A) trunk IMU vertical peak force signature in comparison to the force plate vertical ground reaction force peak; (B) lower-limb IMU braking peak force signature in comparison to the force plate braking ground reaction force peak; (C) lower-limb IMU braking impulse in comparison to the force plate braking impulse (n = 11). N = Newtons; N · s = Newtons per second.

Figure 4: The comparison between force plate (FP) ground reaction force trajectories (black line) and inertial measurement unit (IMU) force signature trajectories (grey line), calculated at the trunk and lower-limb during front foot contact of the delivery stride. (A) is the trunk IMU force signature calculation in the vertical plane, (B) the lower-limb IMU force signature calculation in the vertical plane, and (C) the lower-limb IMU force signature calculation in the braking/propulsive plane. (i) is the mean calculation with standard deviation clouds (force plate = - -; IMU = grey). (ii) displays the SPM{t} : the *t* statistic as a function of time, describing the strength and slope of the relationship between pre- and post-testing measures. The dotted horizontal line indicates the random field theory thresholds for significance, and *p* values indicate the likelihood that a random process of the temporal smoothness would be expected to produce a suprathreshold cluster of the observed size.