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Not as simple as it seems: Front foot contact kinetics, muscle function and ball release speed in cricket pace bowlers

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Abstract

This study investigated the relationship between front foot contact (FFC) ground reaction forces (GRF) during the delivery stride, lower-limb strength, eccentric dexterity and power, and ball release speed (BRS) among pace bowlers. Thirteen high-level male pace bowlers performed double and single leg drop landings; isometric mid-thigh pull; countermovement jump; and pace bowling (two-over bowling spell measuring BRS and FFC GRF). The relationship between assessed variables and BRS was determined via frequentist and Bayesian multiple linear regression. The model including peak braking force was the most probable given the data (Bayes Factor=1.713) but provided only *weak* evidence in comparison to the null model. The results of frequentist and Bayesian modelling were comparable with peak braking force explaining 23.3% of the variance in BRS ($F_{(1, 11)}=4.64$, $P=0.054$). Results indicate pace bowlers with greater peak braking GRF during FFC generally elicit higher BRS. However, the weak relationship between peak braking force and BRS, and the lack of a linear relationship between BRS and other variables, highlights the complexities and inter-individual variability inherent to pace bowling at a high-level. A more individual-focused analysis revealed varied strategies within pace bowlers to deliver the outcome (e.g. BRS) and should be considered in future study designs.

Key Words: eccentric capacity, neuromuscular control, ground reaction forces, isometric strength, drop landing.

Introduction

Cricket players assume roles (i.e. batting, bowling, and fielding) that dictate their primary responsibilities during a game. A bowler’s primary goal is to dismiss opposing batters for as few runs as possible, and is a critical difference between winning and losing teams (Petersen, 2017; Petersen, Pyne, Portus and Dawson, 2008). One strategy pace bowlers adopt to increase the likelihood of dismissing a batter is to maximise ball release speed (BRS), since an increase in BRS decreases a batter’s decision-making and stroke execution time. To maximise BRS, various anthropometric, kinematic, kinetic and physiological variables have been outlined to be advantageous within the literature (King, Worthington and Ranson, 2016; Pyne, Duthie, Saunders, Petersen and Portus, 2006; Wormgoor, Harden and McKinon, 2010). However, conjecture is still present regarding the linear relationship between such variables and BRS.

One biomechanical variable which has been linked to BRS among pace bowlers is the ground reaction force (GRF) experienced during front foot contact (FFC) of the delivery stride (King et al., 2016; Middleton, Mills, Elliott and Alderson, 2016; Phillips, Portus, Davids, Brown and Renshaw, 2010; Portus, Mason, Elliott, Pfitzner and Done, 2004). An increase in peak braking GRF during FFC has been shown to positively correlate with an increase in BRS in elite and high performance pace bowlers (Phillips et al., 2010; Portus et al., 2004). The increase in braking GRFs is linked to a greater deceleration of a pace bowler’s centre of mass (COM) which has previously been shown to be related to higher BRS (Ferdinands, Marshall and Kersting, 2010; Glazier and Worthington, 2014). However, both King et al. (2016) and Middleton et al. (2016) observed no significant relationship between BRS and peak vertical or braking GRF. Interestingly, King et al. (2016) suggested that a large braking impulse during FFC was the best explanatory variable for BRS in elite male pace bowlers. Despite the importance of BRS to pace bowling performance, conjecture still exists regarding the influence of peak GRFs or braking impulses during FFC upon generating maximal BRS. Consequently, the role of GRFs generated during FFC upon BRS requires further assessment to inform cricket authorities, coaches, and players about the global factors that are important for maximising BRS.

The force applied during FFC seems to play a pivotal role in BRS for pace bowlers. Therefore, the relationships between muscular strength and subsequent force output (Bridgeman, McGuigan, Gill and Dulson, 2018; McBride, Triplett-McBride, Davie and Newton, 2002; Peltonen, Walker, Avela, Häkkinen and Hackney, 2018) has led to recommendations of the importance of lower-limb strength, neuromuscular control, or eccentric dexterity (ability to control force) to appropriately attenuate and utilise the forces applied during FFC (Mukandi, Turner, Scott and Johnstone, 2014; Stronach, Cronin and Portus, 2014). However, the extent to which measures of strength and eccentric dexterity relate to BRS are still largely unknown.

To date, the relationship between strength, eccentric dexterity, and BRS among high level pace bowlers is largely unexplored. Both Loram et al. (2005) and Wormgoor et al. (2010) investigated the relationship between lower-limb isokinetic strength and BRS among state premier grade and schoolboy-level pace bowlers but criticism that isokinetic strength does not provide an appropriate representation of the multi-segment neuromuscular control or strength required during pace bowling could be made, rendering the results with limited validity. More recently, Feros, Young and B. O'Brien (2019) attempted to address these limitations by assessing the relationship between a three-repetition maximum half-squat as a measure of strength and BRS upon club standard pace bowlers. However, once again this testing modality may lack the specificity to accurately reflect the range of motion or muscle action (eccentric and concentric versus quasi-isometric) that is common of the FFC limb. As such, it may be beneficial to examine strength during an isometric strength assessment with a more extended knee position as is common during the isometric mid-thigh pull. However, with a focus on the braking ability previously described (Portus et al., 2004), a measure of eccentric control may also be warranted. Therefore, to balance isometric strength assessment, a drop landing assessment focused on the eccentric control (ability to decrease landing force) may provide additional insight into the physical qualities that relate to BRS. This is in addition to the commonly performed CMJ that is also described as an indirect measure of lower-limb (system) power, and to an extent eccentric capabilities (Lockie, Callaghan and Jeffriess, 2015; Lockie, Schultz, et al., 2015). Therefore, it is proposed that a testing battery that includes lower-limb strength (e.g. isometric mid-thigh pull [IMTP]) and eccentric dexterity (e.g. double and single leg drop landings) and lower-limb power (CMJ) is warranted to comprehensively discover if different types of physical capacities have a relationship with BRS.

There is a need to identify the relationship between FFC GRFs (vertical and braking peaks and impulses), measures of lower-limb strength, eccentric dexterity and power, and BRS among pace bowlers, irrespective of their pace bowling technique. Therefore, the purpose of this research was to determine the magnitude of the relationship between FFC GRFs and lower-limb strength, eccentric capacity and power, and BRS, regardless of the technique adopted by the pace bowler. It was hypothesised that a select or combination of GRF, lower-limb strength, eccentric dexterity or power measures would demonstrate at least a moderate relationship with BRS.

Materials and Methods

Participants

Thirteen healthy males were recruited for this study (age = 20.3 ± 4.4 years; mass = 82.4 ± 6.7 kg; height = 1.86 ± 0.05 m). Inclusion criteria were: current or previous involvement in an Australian state cricket development pathway; currently playing first or second grade in an Australian state premier competition; aged 17 years or older; and did not have any existing medical conditions that would be contraindicative to participating in the study. Five left- and eight right-arm pace bowlers participated in the study. All participants, and where appropriate, guardians of participants under 18 years of age, received a clear explanation of the study, including the risks and benefits of participation and provided written informed consent prior to participation. The research was approved by the University Human Research Ethics Committee (Approval #11948).

Procedures

A cross-sectional design was used whereby participants undertook a single testing session in a laboratory setting. Prior to the commencement of data collection, the participant's age, height and body mass were recorded. A general and specific pace bowling warm-up was used for all participants. During the testing session the following assessments were performed in order: double (DLDL) and single leg (SLDL) drop landings; CMJ; IMTP; and pace bowling assessment. Participants were permitted to perform as many practice deliveries as necessary, to become familiarised with the testing environment.

Drop Landing

The DLDL and SLDL was performed as a measure of lower-limb eccentric dexterity (or ability to control force) which provided a quantitative measure of neuromuscular control. Enhanced DLDL and SLDL performance, shown by a decrease in peak vertical GRF, would represent a greater ability to appropriately coordinate the joints to reduce GRF upon landing. An enhanced ability to attenuate and utilise the high GRFs experienced at FFC are critical to optimising technique and ultimately BRS for pace bowlers (King et al., 2016; Middleton et al., 2016; Phillips et al., 2010; Portus et al., 2004). A calibrated portable force plate (400 Series Performance Force Plate, Fitness Technology, Adelaide, Australia) measuring vertical force at 600 Hz was used to assess DLDL and SLDL performance using established procedures (Hargrave, Carcia, Gansneder and Shultz, 2003; Sheppard et al., 2013; Tran et al., 2015). Participants were familiarised to both the DLDL and SLDL assessments by performing three or more practice trials of each prior to data collection. Participants performed two trials of the DLDL from a box height of 0.5 m with hands on hips, stepping forward and were instructed to land as "softly as possible" on both feet (Tran et al., 2015). The SLDL included two trials from the participant's front foot from a box height of 0.3 m (Hargrave et al., 2003). The participant's front foot was based upon their landing pattern during their pace bowling delivery stride. In the SLDL, participants were instructed to step forward off the box with their landing leg with identical instructions as the DLDL (Decker, Torry, Wyland, Sterett and Steadman, 2003). A one-minute rest period was instituted between trials for both the DLDL and SLDL, while a three-minute rest period was utilised between the two measurements. Peak landing vertical force was recorded for all trials. All measures were normalised to body weight (BW) and the best (i.e. lowest peak vertical GRF) of the two trials was used for analysis (DLDL intra-class correlation coefficient [ICC] = 0.96; DLDL coefficient of variation [CV] = 3.17%; SLDL ICC = 0.94; SLDL CV = 1.61%).

Countermovement Jump (CMJ)

The CMJ was used as a measure of lower-limb (system) power. Participants performed the CMJ while standing on the previously described force plate and were familiarised with the CMJ by performing three or more practice trials prior to data collection. The CMJ was performed with a carbon fibre rod (0.25 kg) held at the base of the neck and with the procedures previously described (Secomb et al., 2015). Briefly, participants were instructed to jump as high as possible, and no restrictions were placed on the countermovement range during the eccentric phase of the jump (Lockie, Schultz, Callaghan and Jeffriess, 2014; Nimphius, McGuigan and Newton, 2012). Customised computer software (Ballistic Measurements System, Fitness Technology, Adelaide, Australia) was utilised to determine peak jump height calculated from peak velocity (Moir, 2008). The best (i.e. greatest jump height) of the three trials was used for analysis (ICC = 0.93; CV = 3.01%). Participants performed two trials with a one-minute rest between trials.

Isometric Mid-Thigh Pull (IMTP)

The IMTP is currently part of the physical testing battery outlined by Cricket Australia to measure the strength of all state and state pathway players. The procedures used to perform the IMTP are as previously described (Secomb et al., 2015), on the aforementioned force plate within a customised power rack. The customised power rack allowed the bar to be fixed for each participant. Briefly, participants were instructed to grip the bar in a position similar to that of a second pull of a power clean (Secomb et al., 2015), with an upright trunk position and so that their shoulders were in line with the bar, in their preferred position for the pull (Comfort, Jones, McMahon and Newton, 2015). Participants were instructed to pull as hard as possible on the bar while driving their feet as hard as possible into the force plate (Secomb et al., 2015; Sheppard et al., 2013). Each participant was required to complete two trials of the IMTP, with a two-minute rest between trials. A third trial was performed in the event that a difference in the vertical peak force between the two trials was greater than 250 N (Secomb et al., 2015). The best trials (i.e. highest vertical GRF) for each participant normalised to BW was used for analysis (ICC = 0.99; CV = 1.75%).

Pace Bowling Performance Testing

Data collection. The dimensions of the laboratory allowed each participant to use their normal full-length run-up and follow-through, while bowling deliveries on the equivalent of a standard-sized cricket pitch. An in-ground three-dimensional force plate (9287CA, Kistler Group, Winterthur, Switzerland**)** sampling at 960 Hz was used to collect GRF data during FFC of the delivery stride. FFC corresponded to the first instance at which the vertical GRF exceeded 20 N (Nedergaard et al., 2017). Flooring surface (Mondo S.p.A., Alba, Italy) of the laboratory and on-top of the force platform was consistent. All trials were filmed by a video camera (Apple Inc, Cupertino, USA) recording at 240 Hz from a position perpendicular to the delivery stride to sync FFC on the force plate and ball release using video analysis software (Kinovea – 0.8.15, Kinovea, France) (Feros, Young and O'Brien, 2020). A Stalker Pro II speed radar gun (Stalker Radar, Oregon, USA) was located behind the batting stumps net and aimed at the ball release point to measure BRS.

A two-over spell, comprising 12 deliveries was performed by each participant (Portus, Sinclair, Burke, Moore and Farhart, 2000; Ranson, Burnett, King, Patel and O'Sullivan, 2008; Weerakkody and Allen, 2016). Participants were instructed to deliver each delivery as if under match conditions. A four-minute rest period was provided between the first and second over, as this is the approximate duration of an over within match-play (Portus et al., 2000).

Although infrequent, if a participant failed to land their whole front foot on the in-ground force plate, the trial was disregarded and repeated. All bowlers used a red kookaburra four-piece cricket ball (A.G. Thompson Pty. Ltd., Australia) and wore their own bowling spikes during testing.The peak BRS of each bowler was utilised for analysis (ICC = 0.99; CV = 0.5%)

Data analysis. Discrete kinetic variables were all measured from FFC to ball release, and included peak vertical (maximum force measured in the vertical axis) and braking forces (maximum negative force measured in the anterior-posterior axis), and vertical (calculated as the area under the vertical force time curve) and braking (calculated as the area above/below the braking/propulsive force time curve) impulses. The force platform software (Bioware 5.3.0.7, Winterthur, Switzerland) was used for analysis for each delivery bowled. All kinetic variables were normalised to BW. Further, for a qualitative analysis of athletes of different BRS, a mean with standard deviation cloud of vertical and braking forces of successfully collected trials from the two-overs spell was produced for three pace bowlers using open source package (Pataky, 2012) in the in Python 2.7 using Enthough Canopy 2.1.9 (Enthough Inc., Austin, USA) (Figure 2).

Statistical Analyses

Statistical analyses were conducted using both frequentist and Bayesian techniques. All statistical analyses were performed using the JASP package (JASP Team, 2018, Version 0.8.6) and R statistical computing language (R-Core-Development-Team, 2017). First, a scatterplot matrix with a loess smoother was plot to visualise potential relationships between explanatory variables and BRS. Second, a Bayesian multiple linear regression was conducted with default Jaynes-Zellner-Siow (JZW) priors (Wetzels and Wagenmakers, 2012) to examine the relationships between all combinations of explanatory variables and BRS. In Bayesian regression models, the strength of the evidence for the alternative hypothesis (H_1) against the null hypothesis (H_0) (or models) can be expressed as a Bayes Factor (BF_{10}), which is an odds ratio (Rouder and Morey, 2012). The size of BFs can be interpreted as providing *weak* (BF_{10} = 0-1), *anecdotal* (BF_{10} = 3-9), *moderate* (BF_{10} = 10-29), *strong* (BF_{10} = 30-99) and *very strong* (BF_{10} = 100+) in favour of H_1 compared to H_0 (Jeffreys, 1998). Accordingly, a regression model with a BF_{10} = 30 would indicate that the observed data are 30 times more likely under H_1 compared to H_0. Posterior estimates of regression beta parameters are reported to denote the direction and magnitude of effects and imprecision of model parameters expressed by 95% credible intervals (95% CI_{Bayes}), which denotes that given the data, there is a 95% probability that the regression parameter will fall within this region.

The relationship between BRS and all explanatory variables was also modelled using a frequentist multiple linear regression for comparison purposes. In the frequentist regression model, all possible models were compared against the null model (containing the intercept only) using an information theory approach, whereby the parsimonious model is the model with the lowest information criteria. Owing to known bias in Akaike Information Criteria (AIC) (Akaike, 1974) in small samples, the corrected AIC (AICc) (Hurvich and Tsai, 1989) was used for model comparison purposes. Model selection by AICc is known to be asymptotically equivalent to leave-one-out cross validation (Stone, 1977). Additionally, model size was determined by calculating the relative importance of each parameter using the *relaimpo* package (Grömping, 2006), with the three parameters that explained the most variance retained for modelling [i.e. peak braking force (36%), DLDL (22%) and vertical impulse (16%)]. The AICc for the three-parameter model was then compared against the two and one parameter models, respectively. For each candidate model, the adjusted R^2 value was calculated to express model goodness of fit and 95% bootstrapped confidence intervals (95% CI) were calculated express the imprecision of the regression model parameter estimates.

Results

The descriptive (mean ± standard deviation) results were as follows: BRS = 32.64 ± 1.53 $m \cdot s^{-1}$; IMTP = 3.22 ± 0.48 body weight (BW); DLDL = 2.47 ± 0.36 BW; SLDL = 1.69 ± 0.1; jump height = 0.39 ± 0.04 m; peak vertical force = 6.80 ± 1.08 BW; peak braking force = -4.16 ± 0.96; vertical impulse = 0.31 ± 0.03 BW·s; braking impulse = -0.16 ± 0.03 BW·s. In comparison to all other probable models, Bayesian linear regression indicated that the model including peak braking force was the most probable given the data. However, it provided only *weak* evidence in favour of H_0 compared to H_1 (BF = 1.713). Bayesian posterior estimates and 95% CI_{Bayes} for the peak braking force model indicate that for each one-unit change in peak braking force there was a -0.70 $m \cdot s^{-1}$ (95% CI_{Bayes}: [-1.54, 0.14]) change in BRS.

The results of frequentist and Bayesian modelling were comparable, and the frequentist multiple linear regression model hierarchy is reported in Table 1. The model containing only peak braking force as an explanatory variable was parsimonious, as indicated its low AICc value compared with all other candidate models. Peak braking force explained 23.3% of the variance in BRS ($F_{(1, 11)} = 4.64$, $P = 0.054$), where a one unit change in peak braking force was associated with a -0.98 $m \cdot s^{-1}$ (95% CI: [-1.84, -0.10]) change in BRS (Figure 1).

INSERT TABLE 1 ABOUT HERE

***INSERT FIGURE 1 ABOUT HERE ***

The mean force-time traces of FFC with standard deviation clouds from two-overs is presented in Figure 2. The three bowlers have practically meaningfully different BRS but have produced these with different GRF strategies present. It is noted that the time to peak braking forces are more similar than the patterns present in the time to peak vertical forces. Further, the shapes of the vertical force-time curves a distinctly unique despite relatively similar peaks for vertical and braking forces owing to help explain the frequentist and Bayesian results displaying only *weak* relationships or explained variance (23.3%) between BRS and peak braking force.

***INSERT FIGURE 2 ABOUT HERE ***

Discussion

This study investigated the relationship between FFC GRFs, lower-limb strength, eccentric dexterity, power, and BRS among pace bowlers. The findings of the current investigation provide some (although weak) evidence that greater peak braking GRF during FFC is associated with higher BRS. The strength of this relationship, and no other association between lower-limb strength, eccentric capacity, or power and BRS, may suggest that the inter-individual variation of pace bowling techniques within the small participant pool limited the ability to definitively determine global characteristics associated with increased BRS as qualitatively exampled in Figure 2. Therefore, a more individual approach to the generation of BRS for pace bowlers, utilising a larger sample size may be needed to ascertain the characteristics associated with increased BRS.

The evidence in support of the null model between peak GRF during FFC and BRS was rejected, indicating that an increase in peak braking GRF (i.e. a lower negative number) was associated with a higher BRS. Portus et al. (2004) and Phillips et al. (2010) also observed a positive relationship between peak braking GRF and BRS among elite and high performance pace bowlers. A higher braking GRF during FFC should translate to greater deceleration of a pace bowler's COM during FFC to ball release, which has previously been associated with an increased BRS among high performance pace bowlers (Ferdinands et al., 2010; Glazier and Worthington, 2014). Greater deceleration of a pace bowler from FFC to ball release would suggest that a greater amount of kinetic energy is available to be transferred from the run-up to the trunk and arm segments during bowling, ultimately culminating in a higher BRS (Ferdinands et al., 2010; Kreighbaum and Barthels, 1985). Importantly, peak braking GRF only explained 23.3% of the variance in BRS, indicating that 76.7% is unexplained. The largely unexplained variance in BRS may be a consequence of the complexities (i.e. required multi-segment co-ordination) and characteristics (i.e. interaction of anthropometrics and physical capacities) necessary for maximum BRS among pace bowlers. Interestingly, recent research from Felton, Yeadon and King (2020) has advocated for an individualised approach to maximising BRS via computer modelling. Felton et al. (2020) demonstrated a 3.5 m/s improved in BRS by optimising elements of an elite fast bowler's technique, via a validated computer model. However, whether an individual's musculoskeletal system is able to adopt the optimised technique will always be the limitation of computer modelling. Nevertheless, the outlined relationship between peak braking GRF and BRS does still support some importance of GRF during FFC to BRS.

All other measured GRF variables during FFC supported the acceptance of the null model. The acceptance of the null model is in opposition to the findings of Portus et al. (2004), Phillips et al. (2010), and King et al. (2016), whom have all reported one or multiple relationships between peak vertical GRF, vertical impulse or braking impulse during FFC and BRS in elite pace bowlers. The lack of agreement with previous literature may suggest that the complex interaction between anthropometric, physical, physiological, and pace bowling technique may not allow for a constant, global relationship with BRS to be present. This perspective is supported by Salter, Sinclair and Portus (2007), who outlined in a pilot investigation that a within-bowler analysis of a single elite pace bowler could explain 87.5% of the variance in the individual pace bowler's BRS, while a between-bowler analysis of 20 elite bowlers revealed no significant relationships. It would be anticipated that greater between-bowler variability would be present in lower-level pace bowlers, which may further suggest the need for a within-bowler analysis for the participants of the current investigation. Taken together, these findings may illustrate the need for an individual analysis of a pace bowler to best identify the factors associated with higher BRS.

The results of the current investigation indicated a trivial relationship between the IMTP (a measure of lower-limb strength) and BRS existed. The lack of a relationship between IMTP and BRS is similar to the results of investigations which have used lower-limb isokinetic (Loram et al., 2005; Wormgoor et al., 2010) and three-repetition maximum half-squat (Feros et al., 2019) testing as a measure of strength. The variance in how a pace bowler will seek to generate maximum BRS and the influence of their strength upon these numerous characteristics may limit the ability of a cross-sectional analysis to demonstrate key relationships. For example, run-up velocity (Feros et al., 2019; Worthington, King and

Ranson, 2013), FFC GRFs (King et al., 2016; Portus et al., 2004), and front knee angle during FFC to ball release (Wormgoor et al., 2010; Worthington et al., 2013) have all been associated or shown to have a relationship with increased BRS. All these technical qualities require a transfer of one's strength in a generic assessment into a skilled performance (Suchomel, Nimphius and Stone, 2016). Hence, a single test measure of strength may not be appropriate for identifying a relationship with BRS when undertaking a cross-sectional analysis without consideration of the variation in how pace bowlers will attempt to generate maximal BRS. Nonetheless, enhanced lower-limb strength, such as that measured by the IMTP, has been associated with capacities that relate to cricket performance, such as jumping (Suchomel et al., 2016), acceleration (Lockie, Murphy, Schultz, Knight and Janse De Jonge, 2012) and change of direction (Spiteri et al., 2014) performance but may be a function of a more complex relationship than simply linear as is characteristic of the non-linear dynamical system associated with sporting skill.

In the current study, a trivial relationship existed between drop landing performance (utilised as a measure of eccentric dexterity) and BRS. High magnitudes of braking GRF would be hypothesised to necessitate greater eccentric dexterity to effectively control eccentric demand of FFC; however, the results of this study do not support this hypothesis. Perhaps a more appropriate measure of eccentric dexterity is required, one which involves greater emphasis on multi-planar coordinative control in addition to the primarily uniplanar measure chosen in this study. Alternatively, the magnitude of the vertical component of the GRF during the drop landing task may not appropriately reflect the high GRF values present during FFC of the delivery stride. This potential lack of specificity with regards to the drop landing test may fail to provide enough of a stimulus to allow for differentiation between faster and slower pace bowlers. Additional research is required to determine whether other measures of eccentric dexterity may relate to BRS or, as discussed with measures of strength, a more refined consideration of implication of movement strategy is likely required.

Lower-limb power as measured by the CMJ exhibited a trivial relationship to BRS and is supported by the research findings of Feros et al. (2019) who also reported no relationship between maximum countermovement jump height and BRS among club-standard pace bowlers. Interestingly, Pyne et al. (2006) reported a negative linear relationship between single leg Smith machine CMJ height and BRS among both first-class senior and junior representative pace bowlers, which suggests greater jump height was related to a slower BRS. However, it was recommended that the single legged CMJ was not an appropriate test for pace bowlers, as the typical error of measurement was 40% greater than the static single legged squat jump also performed in the testing protocol. The lack of a meaningful relationship to CMJ and BRS does not discount the importance in pace bowlers, as CMJ power has been shown to have strong relationships to sprint acceleration (precurser to FFC), however, the subsequent ability to arrest this momentum for transfer to the ball is likely determined by a combination of physical capabilities dependent on the coordinative strategy chosen by the pace bowler. That is whether they employ a more hip- or knee-dominant strategy. The repeated discussion on the importance of movement strategy has been suggested in prior research. As shown in Figure 3, there is a large amount of variance in the identified front lower limb techniques (or strategies) in BRS and peak braking force. As such, it seems similar to the athletes of this study (Figure 2) there are many individuals that have varied bowling success within each strategy but it is likely each strategy when combined together could explain the lack of association between specific physical capacities and the outcome variable of BRS as each athlete may be attaining the BRS in a unique way.

***INSERT FIGURE 3 ABOUT HERE ***

There are certain limitations of this study. No kinematic data was collected and therefore future research should assess whether a relationship between pace bowling kinematics and BRS is present via an appropriate statistical approach. Additionally, the participant numbers utilised in this study were low but still provided hypothesis generating information through an individual athlete analysis approach; and are of similar participant size to previous studies which have investigated the biomechanics and BRS of pace bowlers (Glazier, Paradisis and Cooper, 2000; Portus et al., 2000; Zhang, Unka and Liu, 2011).

In conclusion, BRS was shown to have a weak relationship with peak braking GRF during FFC. This relationship may suggest that greater deceleration of a pace bowler from FFC to ball release is generally advantageous by allowing for a larger amount of kinetic energy to be transferred from the run-up, through the body, to the ball at the point of release, resulting in a higher BRS. Measures of FFC GRF, lower-limb strength, eccentric dexterity or power exhibited only trivial relationships to BRS among pace bowlers. The lack of any other relationships between assessed measures and BRS may suggest that the complexities and characteristics of pace bowling, which will vary between individuals, may limit the ability to identify global variables associated with BRS. Pace bowlers will utilise various components of their physiology, anthropometry, and strength throughout their pace bowling action in an attempt to maximise BRS. This may indicate that an individual approach may be required to best determine the relationship between BRS and a pace bowler's biomechanics.

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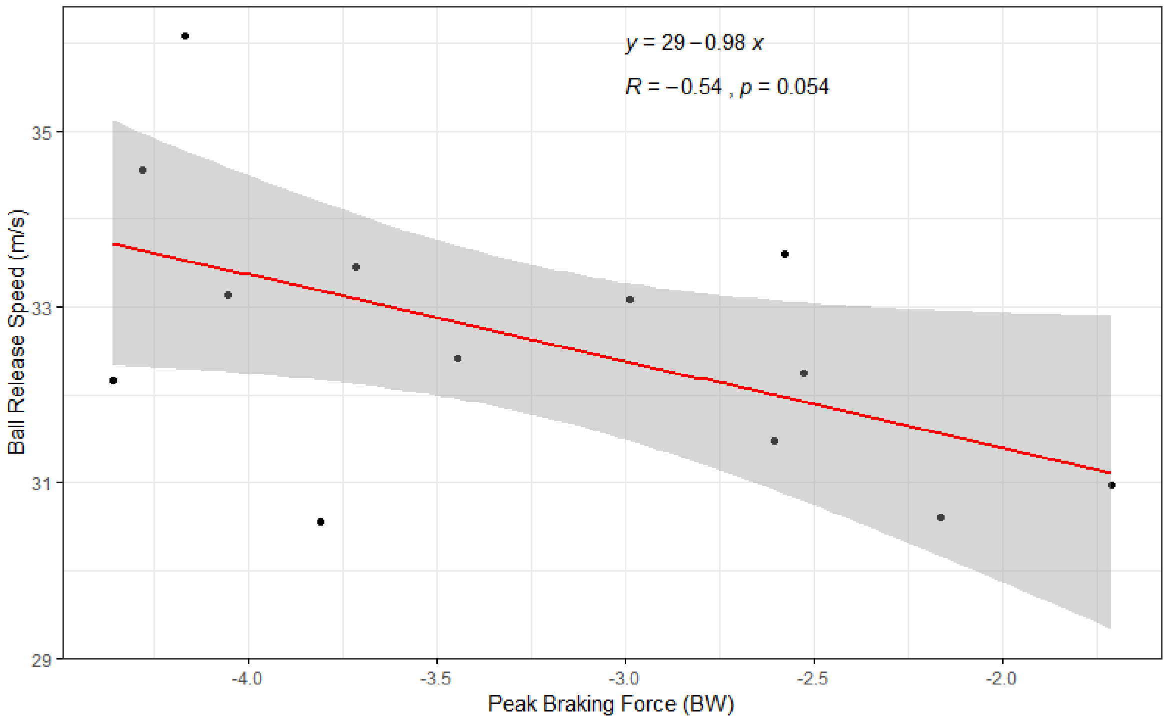

Figure 1: Relationship between peak braking force and ball release speed.

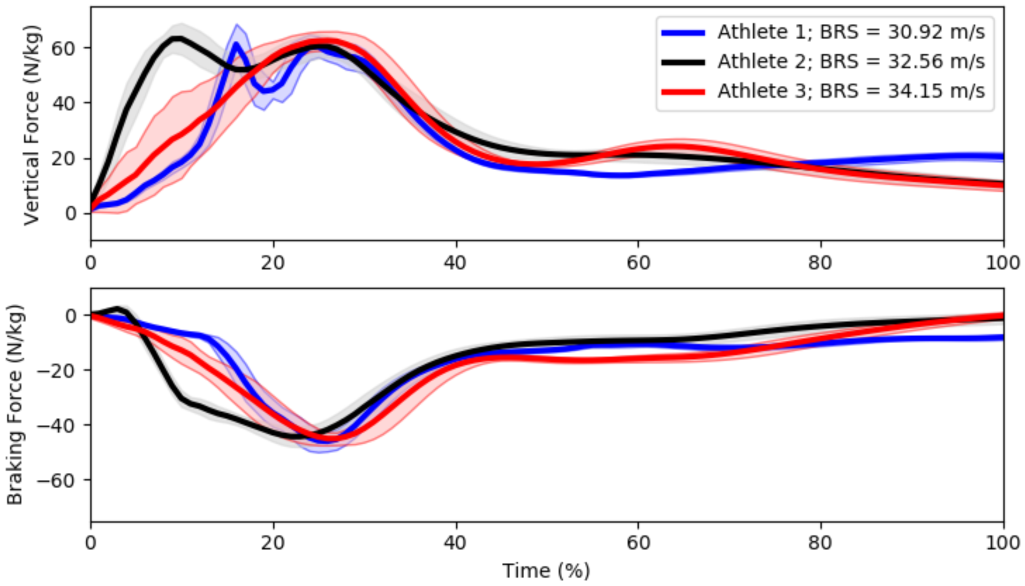

Figure 2. Mean and standard deviation cloud of successful trials of two-overs for three atheltes of varying ball release speed capabilities. Notably, there are large differences in the qualitative shape of the force-time curves, particularly of vertical force despite relatively similar peak vertical and braking forces. Further, notable differences in time to peak vertical force is present. Such differences in the force-time curves may be indicative of previously discussed variations in front lower limb technique (Portus et al., 2004) or movement strategy.

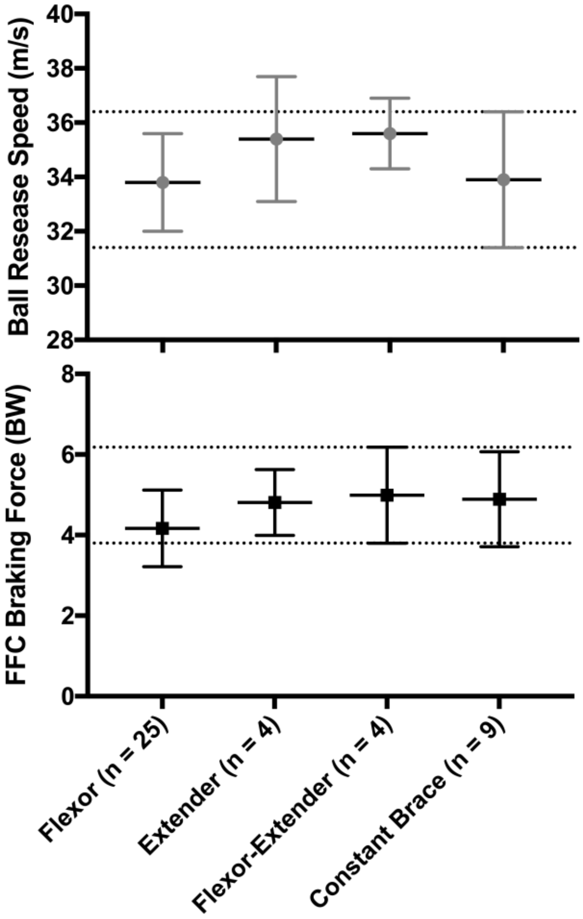

Figure 3. Previous data from Portus et al. 2004, demonstrated large variation in ball release speed (BRS) across four "front lower limb technique groupings" and potentially explanatory of the current weak relatioinship between braking peak force and BRS is the variability within these groups. Therefore, future research may seek to consider the potential requirements of each movement strategy as subgroups.

Table 1: Parameter estimates table for frequentist regression modelling.

Parameter	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**
Intercept	32.64	[31.68, 33.61]	29.43	[27.20, 32.24]	26.69	[19.45, 33.13]	19.16	[7.29, 31.04]
Peak Braking force (BW)			-0.98	[-1.84, -0.10]	-0.97	[-1.97, 0.04]	-0.84	[-1.80, 0.12]
Vertical Impulse (BW.s)							20.31	[-8.12, 48.75]
Double Leg Drop Landing (BW)					1.13	[-1.01, 3.28]	1.60	[-0.53, 3.72]
Observations	13		13		13		13	
R^2	0.000		0.297		0.382		0.521	
Adjusted R^2	0.000		0.233		0.259		0.362	
AICc	53.2		52.110		57.756		57.015	

CI = Confidence interval; AICc = Corrected Akaike Information Criteria; BW = Body weight; BW.s = Body weight per second