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Abstract

This study examined the relationships between physical capacity, bowling technique and ball speed in high-level cricketers. Kinetic, kinematic and temporal aspects of bowling technique were three-dimensionally analysed in 20 fast-bowlers (professional n=4, elite academy n=9 and state premier cricket n=7). Physical capacity measures included 30 m sprint, vertical jump, isometric mid-thigh pull (IMTP), bench pull and 2 km running time-trial. Correlations revealed technique factors associated with ball speed were; bowling action duration (r=-0.639, p=0.002), run-up velocity (r=0.616, p=0.004), back foot contact (BFC) time (r=-0.608, p=0.004), front foot contact (FFC)-ball release (BR) duration (r=-0.602, p=0.005), delivery stride phase acceleration (r=-0.582, p=0.007), delivery stride duration (r=-0.547, p=0.012), time of peak horizontal braking force (r=-0.538, p=0.014), peak pelvis COM velocity (BFC-BR) (r=0.469, p=0.037) and peak vertical GRF time (r=-0.461, p=0.041). Physical capacities correlated with ball speed were; 10-30 m split (r=-0.554, p=0.011), 30 m sprint (r=-0.482, p=0.031) and IMTP (r=0.471, p=0.036). Stepwise regression showed bowling action duration and 10-30 m split explained 54% (p=0.001) of variation in ball speed. Accordingly, increased ball speed was associated with faster run-ups, shorter BFC times and abrupt application of FFC GRF. Coaches should also consider sprint speed and lower-body strength as important modifiable factors for fast-bowlers.

Key words: Biomechanics, performance, strength and conditioning, sports

Introduction

Successful performance in cricket fast-bowling is multi-factorial, however ball speed is commonly perceived to be of specific importance (Glazier et al., 2000). Faster ball speeds reduce the amount of time a batsman has to make an effective decision in their stroke play, increasing the likelihood of a lost wicket and reducing run-scoring (Zhang et al., 2011). Fast-bowlers who achieve superior ball speeds demonstrate better bowling averages and strike rates (Malhotra and Krishna, 2017) and higher ball speeds are reported in high-level fast-bowlers compared to amateurs (Middleton et al., 2016). To optimise performance, it is important to understand the mechanisms for maximising ball speed. Interestingly, bowling technique analysis remains the predominant focus in research in this area (Portus et al., 2000, Worthington et al., 2013b, Portus et al., 2004). However, given the physically demanding nature of fast-bowling (Johnstone et al., 2014), the relationship between physical capacities and ball speed may also be of interest. Accordingly, a holistic understanding of the inter-relationships between technical proficiency and physical capacity is required to maximise ball speed.

Fast-bowling is physically demanding, commencing with a 15-30 m run-up at speeds of 4.0-6.0 $m\cdot s^{-1}$ (Glazier and Wheat, 2014). Following the run-up, an explosive bowling action occurs where peak vertical ground reaction forces (GRFv) of up to 9.5 x bodyweight (BW) (Hurrion et al., 2000) are experienced within 0.05s of front foot contact (FFC) (Worthington et al., 2013a). In turn, this sequence may be repeated over 120 times in a day's play (Orchard et al., 2015) and more than 300 times in a first-class match (Orchard et al., 2009). To withstand these stressors and optimise performance, athletes require increased strength and fitness (Johnstone et al., 2014). In turn, faster ball speeds have been associated with greater muscle mass (Portus et al., 2000), increased lower-body power (Pyne et al., 2006), faster sprint speed (Feros et al., 2019) and superior muscular strength of the shoulder extensors and internal rotators (Mabasa et al., 2002, Wormgoor et al., 2010). However, previous research is typically unifocal, reporting individual physical capacities without addressing the diversity of modifiable fitness needs in high-level players. A better understanding of the association between physical capacity measures and ball speed may guide appropriate training and testing for fast-bowlers.

While fitness may be important to optimise fast-bowling performance, the mechanical determinants of force generation from bowling technique are critical to maximising ball speed. Fast-bowling requires rapid generation of force to impart high release velocities onto the ball (Glazier and Wheat, 2014). Technique factors that increase the efficiency and transfer of linear momentum with effective use of elastic qualities through the kinetic chain and into the ball are important to generate the requisite forces to release the ball at high speeds. For example, increased run-up speed (Duffield et al., 2009, Ferdinands et al., 2010, Middleton et al., 2016), temporal measures such as time between FFC and BR (Feros, 2015), shoulder orientation at FFC (Wormgoor et al., 2010), greater front knee extension angle at FFC and ball release (BR) and front leg horizontal braking impulse (King et al., 2016) are historically highlighted as being associated with fast-bowling performance. Given the rapid application (Worthington et al., 2013a) and high magnitude of forces (Hurrion et al., 2000) in the fast-bowling action, it is plausible that changing specific physical capacities, such as lower-body maximal and explosive strength as well as muscle cross-sectional area, may allow fast-bowlers to optimise these crucial technical components. Further, by influencing rate of force development (Aagaard et al., 2002) and muscle-tendon unit stiffness (Tillin et al., 2012, Ryan et al., 2009) during the BFC and FFC phases (Johnstone et al., 2014, Felton et al., 2020), the integration of physical capacity and technique may provide scope for increased ball speeds. Accordingly, the testing and development of fast-bowling performance requires concurrent understanding of both physical and technical parameters.

Many national cricket governing bodies develop and implement standardised physical and technique testing protocols; though often lack evidence to guide training interventions or player development. A common discussion point for many strength and conditioning practitioners is that existing literature related to fitness and ball speed has limitations for practical interpretation. For example, typically these studies use single-joint isokinetic dynamometry (Wormgoor et al., 2010) to test strength which is often not accessible, practical or commonly used by strength and conditioning coaches with elite fast-bowlers (Scott and Herridge, 2018). Furthermore, Harman (2008) argues biomechanical movement specificity is a key element of athletic performance test selection and thus multi-joint field-based player assessments undertaken at the elite level are more specific to dynamic sporting actions like sprinting and jumping than single-joint isokinetic dynamometry. Regardless, simultaneously incorporating contemporary and widely used assessments of physical capacity and technique parameters to understand bowling speed provides a more holistic and actionable view not yet reported in the literature. Therefore, this study investigated the association between physical capacity measures (assessed via the Australian Cricket Performance Program [ACPP] Physical Performance Testing battery) and the mechanical factors of bowling technique using three-dimensional motion analysis, with ball speed in cricket fast-bowlers.

Materials and Methods

Participants

A priori power analyses were conducted (G*Power 3.1.9.4) (Faul et al., 2007) for two-tailed bivariate normal model correlation with H1 $r=0.6$, $\alpha=0.05$, $1-\beta$ error probability = 0.8 to determine the required sample size (19 participants). The anticipated effect size was determined from previous literature [run-up speed (Duffield et al., 2009)], [COM acceleration over stride phase (Ferdinands et al., 2010)] and [horizontal braking impulse (King et al., 2016)]. Accordingly, 20 male fast-bowlers (22.1 ± 4.4 years, 1.91 ± 0.07 m; 85.5 ± 9.5 kg) volunteered to participate in this study. All participants (or guardians) gave prior written informed consent. Participants were included if they were injury-free and part of an Australian state team (n=4, 26.0 ± 4.4 years), a state U17 or U19 team (n=9, 18.3 ± 1.1 years) or a state premier cricket team (n=7, 24.9 ± 3.3). All participants were undertaking 1-3 strength and conditioning sessions per week prior to testing and had at least one year of strength and conditioning training history. Ethics approval was granted by the University Human Research Ethics Committee (ETH18-2374).

Overview

Testing involved two sessions and was conducted at the end of the competition season to ensure appropriate match fitness. At the first session, physical capacity assessments were conducted in a high-performance training centre (outlined below). The second session involved full-body biomechanical analysis of bowling technique in a research laboratory. All players presented in a rested state, were injury free at the time of testing and undertook a standardised 20-minute warm-up prior to testing including dynamic stretching, running drills and practice bowling.

Physical capacity tests

Physical capacity tests were based on those conducted as part of the ACPP Physical Performance Testing battery and all players were familiar with the tests. Lower-body power was assessed using a vertical jump (VJ) test with arm swing, where participants attempted to gain maximum height by hitting the highest vane possible with their hand on a yardstick with 1 cm increments (Swift Performance, Wacol, Queensland, Australia) (Markovic et al., 2004), performing three trials with the highest value recorded. This method demonstrates appropriate reliability (intrasession intraclass correlation coefficients [ICC]=0.80-0.94) (Nuzzo et al., 2011). Lower-body maximal strength was measured using an isometric mid-thigh pull (IMTP) (Thomas et al., 2016). The test was performed using a one-dimensional force plate sampling at 600Hz (400S, Fitness Technology, Skye, South Australia). The IMTP is a valid and reliable measure of lower body strength (intrasession ICC=0.98 and intersession ICC=0.89) (De Witt et al., 2018, Townsend et al., 2017). The highest peak GRFv observed from three trials was recorded as an absolute value (N) and normalised for BW. To determine upper-body strength, a one repetition maximum (1RM) bench pull test was completed. The athletes lay prone on a bench and used a pronated grip, commencing from a full hang starting position. Supervised by an experienced coach, each athlete completed increasingly heavier single repetitions until a 1RM was achieved. Aerobic fitness was determined using a 2 km running time trial (2 km-TT) which was completed on a road-based course with the total time recorded to the nearest second. To assess speed, a maximal 30 m sprint test was conducted on an outdoor synthetic track. Participants performed three trials from a two-point standing start position with split times recorded using timing gates (TC Timing System, Brower Timing Systems, Draper, Utah, USA). The fastest 10 m, 10-30 m split and 30 m sprint times from any of the separate trials were recorded for analysis.

Technique analysis

Bowling technique analysis was performed in an indoor biomechanics laboratory with a run-up space of 19 m and a regulation length pitch. A 20-camera Qualisys motion analysis system (Oqus 3+/7+, Qualisys, Göteborg, Sweden) operating at 240 Hz and four three-dimensional (3D) force plates sampling at 2400 Hz and with a combined dimension of 0.8 m x 1.2 m (Kistler AG, Winterthur, Switzerland) captured kinematic and ground reaction force (GRF) data for the FFC phase. Force plates were embedded into the ground under a 12 mm thick synthetic cricket pitch running the length of the laboratory. A radar (Stalker ATS II, Richardson, Texas, USA) was mounted on a gantry 3.4 m above the ground and 4.9 m behind the bowler's arm to record ball speed. Following the warm-up, participants were recorded while bowling 12 maximum intensity deliveries, four balls each at 'full', 'good' and 'short' lengths to a right-handed batter (Spratford et al., 2007).

A customised marker set consisting of individual 14 mm spherical markers and semi-rigid clusters was used to define segment parameters and track movements during motion capture. As shown in Figure 1, individual markers were attached directly to the skin or to the shoes of each participant to identify bony landmarks used to determine joint and segment parameters. Marker locations were: at the head of the first, third and fifth metatarsals, calcaneus, medial and lateral malleoli, medial and lateral epicondyles of the femur, anterior superior iliac spines, lateral edges of the frontal and parietal eminences, jugular notch, xiphoid process, C7, T10, acromion processes, lateral epicondyles of the humerus, styloid processes of the radius and ulna, and base of the third metacarpal. Additional individual markers were placed at the lateral midpoint of the upper arm and forearm to assist with tracking motion. Clusters with four markers each were attached over the pelvis, thighs and shanks to assist with tracking motion. The pelvis cluster included a marker to identify the location of the sacrum. A pair of reflective stickers were attached to a regulation 156 g cricket ball (Kookaburra, Moorabbin, Victoria, Australia) to allow motion capture of the ball. Kinematic and GRF data were acquired and processed through specialised software (Qualisys Track Manager v2.16, Qualisys, Göteborg, Sweden) and exported for further analysis in Visual3D (C-Motion v5.0 Professional, Germantown, Maryland, USA). A Butterworth low-pass filter was applied to the data with a cut-off frequency of 10 Hz, as determined by a residual analysis (Winter, 2009). Segments were created for the pelvis, trunk and head, and bilaterally for the thigh, shank, foot, upper arm, forearm and hand, establishing a full-body kinematic model. Local coordinate systems were established for each segment, as well as a global coordinate system relative to the laboratory. All coordinate systems, segments and joints were defined based on the standards outlined by the International Society of Biomechanics (Wu and Cavanagh, 1995, Wu et al., 2002, Wu et al., 2005).

For each trial, temporal events were defined at back foot contact (BFC), FFC and BR. For all participants BFC and FFC were defined as the first instance when the calcaneus marker was at its lowest vertical position at or after initial contact during the ground contact phase. BR was defined as the first frame the ball and the joint centre of the bowling wrist increased by more than 20 mm relative to the distance in the previous frame (Worthington et al., 2013b). Bowling action duration was defined as the time between BFC and BR, delivery stride duration was the time between BFC and FFC, and BFC time was the duration between the first instant of visually observed contact with the ground to the last instant of visually observed weight bearing contact with the ground.

The 3D linear and angular kinematic data in Table 1 and Table 2 were calculated at each event, and GRF data in Table 1 were acquired during FFC. Force data were only included for analysis if the entire front foot landed within the force plate boundaries. The centre of mass (COM) of the pelvis segment was used to represent the whole-body COM, with velocity and acceleration measured with respect to the global anterior-posterior axis. Pelvis and shoulder alignment angles were observed in the transverse plane with a zero-point aligned with the bowling crease and positive rotation occurring clockwise for right-handed bowlers and counter-clockwise for left-handed bowlers. All other variables were normalised between right and left-handed bowlers.

Statistical analysis

As based on previous fast-bowling research (Spratford et al., 2007) the mean of the 12 bowling trials for each participant was used to determine the value of each technique parameter in further analysis. However, technical difficulties meant that GRF parameters were missing from some trials for some participants. In these instances, the mean of all available GRF trials were used to determine GRF parameters while all 12 trials for all other variables were used for the participant. For all physical capacity measurements, the best trial was recorded for analysis. Stem and leaf plots and frequency tables were visually inspected to screen for any data miscoding. Three outliers were identified following visual inspection of scatterplots and the Shapiro-Wilk's test ($p < 0.05$), including a VJ, 2 km TT and mean peak horizontal braking force. All other variables were normally distributed (Shapiro-Wilk's test: $p = 0.062 – 0.970$). All statistical analyses were performed using Statistical Package for Social Sciences software v25 (IBM, New York, USA) with significance set at $p < 0.05$.

To determine associations between ball speed and each of the dependent variables, three different sets of Pearson's product-moment correlation coefficient tests (two-tailed) were used (temporal and kinetic determinants, kinematic determinants and physical fitness determinants). Correlation magnitudes were based on the guidelines of Hopkins et al. (2009); < 0.1: *trivial*, 0.1 ≤ *small* < 0.3, 0.3 ≤ *moderate* < 0.5, 0.5 ≤ *large* < 0.7, 0.7 ≤ *very large* < 0.9, ≥ 0.9: *extremely large*. Alpha was not corrected for multiple comparisons as this was primarily an explorative study, any significant findings therefore require further confirmation in independent studies.

A stepwise regression was performed to predict the outcome variable (ball speed) from the predictor variables. Additionally, all predictor variables were assessed for multicollinearity with exclusion based on a threshold of $r \geq 0.8$ and all cases meeting these criteria were reduced by removing the variable with a lower correlation to ball speed (Slinker and Glantz, 1985). Following this process, only 10 variables were considered for stepwise regression. These were: bowling action duration, time of peak horizontal braking force, pelvis COM velocity at BFC, peak horizontal braking force, lumbar extension at BFC, 10–30m sprint split time, shoulder rotation at BFC, peak trunk lateral flexion, VJ and normalised IMTP. The outputs from the regression analysis consisted of the R^2 value which represented the proportion of variance in the dependent variable that could be explained by the independent variables, the adjusted R^2 value representing the percentage of the response variable variation that is explained by the model, the F value and degrees of freedom and the coefficients for the constant and independent variable.

Results

Mean ball speed for the 20 participants was 34.3 ± 1.9 (range 30.4-37.9) $m \cdot s^{-1}$. For the Australian state-level fast-bowlers it was 34.0 ± 3.1 (range 37.9-30.4) $m \cdot s^{-1}$, for the state U17 or U19 fast-bowlers it was 34.6 ± 1.4 (range 36.8-33.1) $m \cdot s^{-1}$ and for the state premier-level cricket fast-bowlers it was 34.2 ± 2.0 (range 37.3-31.6) $m \cdot s^{-1}$. Using the action classification systems described by Portus et al. (2004) (pelvis COM velocity at BFC in parenthesis), nine of the participants were identified as using a mixed bowling action (5.43 ± 0.57 $m \cdot s^{-1}$), eight were semi-open (5.57 ± 0.62 $m \cdot s^{-1}$), two had side-on actions (5.59 ± 0.09 $m \cdot s^{-1}$) and one used a front on technique (5.05 $m \cdot s^{-1}$).

Analysis of kinetic and temporal components (Table 1) revealed significant *large* correlations ($p<0.05$) between ball speed and bowling action duration, pelvis COM velocity at BFC, BFC time, FFC-BR phase duration, pelvis COM acceleration (delivery stride phase), delivery stride phase duration and time of peak horizontal braking force as a percentage of the bowling action. *Moderate* significant correlations ($p<0.05$) existed between ball speed and pelvis COM peak velocity (BFC–BR) and time of peak GRFv as a percentage of the bowling action.

None of the kinematic variables (Table 2) collected were found to have a significant correlation ($p>0.05$) with ball speed. However, three of these variables (lumbar extension at BFC, shoulder rotation at BFC, peak trunk lateral flexion) met the criteria for consideration in stepwise regression.

For physical testing (Table 3), a significant *large* association ($p<0.05$) existed between ball speed and the 10-30m sprint split time. Significant *moderate* correlations ($p<0.05$) also existed between ball speed and 30 m sprint time and absolute IMTP. No other significant correlations were evident between ball speed and the remaining physical capacity assessments ($p>0.05$).

Correlation analysis also revealed inter-relationships between physical capacity and some fast-bowling technique variables. Absolute IMTP, used to assess lower body maximal neuromuscular strength, was shown to correlate with pelvis COM velocity at BFC ($r=0.450$, $p=0.047$) and pelvic COM acceleration (delivery stride phase) ($r=-0.454$, $p=0.045$).

A stepwise regression (Table 4) was calculated to determine association with ball speed ($F\ (2,17) = 10.111$, $p=0.001$) and the identified variables accounted for 54% ($r^2=0.543$) of variation in ball speed. Bowling action duration ($p=0.009$) and 10 – 30 m sprint split time ($p=0.034$) were significant predictors of ball speed in the model. The best model of fit (95% confidence) for ball speed was 57 ($m\cdot s^{-1}$) – 27 x (bowling action duration [s]) – 6 x (10 – 30 m sprint split time [s]). Confidence intervals (95%) for the coefficient estimates were -47 to -8 for bowling action duration and -12 to -1 for 10 – 30 m sprint split time. Visual observation of P-P plot of regression standardized residuals confirmed normality and homogeneity of variance.

Discussion

This study reports the relationship of technique and physical capacity measures with ball speed in high-level fast-bowlers. Technique factors associated with ball speed were increased run-up speeds, shorter BFC times, decreased duration of key phases of the bowling action and larger and greater declaration between BFC and FFC caused by abrupt application of peak GRF. Furthermore, sprint speed and lower body strength were significantly associated with higher ball speeds. The stepwise regression analysis indicated two variables (bowling action duration and 10 – 30 m sprint split) collectively explained 54% of the variation in ball speed.

Similar to previous studies, run-up velocity, particularly at BFC ($r=0.616$, $p=0.004$), had a *large* association with increased ball speeds (Ferdinands et al., 2010, Phillips et al., 2010, Middleton et al., 2016, Duffield et al., 2009). Furthermore, BFC time showed a *large* correlation with ball speed, indicative of reduced ground contact time and potentially accompanying braking forces. However, further investigation into the relationship between horizontal braking forces during the back foot contact phase and ball speed is required. As GRF data was not captured for the BFC phase, this analysis was not possible in the current study. Generating and retaining linear momentum during the run-up and the BFC phase seems important for fast-bowling performance (Ferdinands et al., 2010, Phillips et al., 2010, Middleton et al., 2016, Duffield et al., 2009). This is likely because the run-up serves as an essential precursor to subsequent impulse generated at FFC. Poor generation of linear momentum during the run-up, and/or loss of momentum during the BFC phase, results in less momentum transferred through the kinetic chain during the bowling action and subsequently onto the ball at release (Ferdinands et al., 2010). Furthermore, pelvis COM acceleration during the delivery stride phase had a *large* negative correlation with ball speed. These findings align with previous research indicating faster ball speeds were associated with earlier application of GRF (Portus et al., 2004), higher impulse, and larger mean loading rates (King et al., 2016). Evidently, bowlers in the current study who more rapidly applied GRF during FFC yielded significantly faster ball speeds.

Temporal technique variables such as faster bowling action duration, delivery stride duration and FFC-BR phase duration were associated with increased ball speed. Namely, bowling action duration was one of two key components of the step-wise regression analysis, emphasising the importance of minimising bowling action duration for maximised ball speed. Feros (2015) reported similar results regarding FFC-BR phase duration (r=-0.45), though there was no association with delivery stride duration (r=0.022). A direct comparison with the current results is not possible as BFC time and bowling action duration were not reported (Feros, 2015). According to Glazier and Worthington (2014), the FFC-BR phase represents the most important component of the bowling action, as this is where the mechanics of the front leg and the geometry of GRF influence ball speed the most. Their results suggested the magnitude of change in COM velocity rather than the duration of the FFC-BR phase, was most strongly correlated to ball speed. While change in magnitude was not specifically assessed in the current study, the findings regarding pelvis COM deceleration during the delivery stride phase supports this suggestion. Furthermore, there was a *large* relationship between pelvis COM deceleration and ball speed (r=0.582, p=0.007) evident during the delivery stride phase. Ferdinands et al. (2010) similarly report that COM deceleration in both the delivery stride phase and the FFC-BR phase were strongly predictive of ball speed (r=0.666). In relation to the mechanics, higher ball speeds are associated with rapid COM deceleration between BFC and BR. This COM deceleration is the by-product of the momentum generated during the run-up and subsequent magnitude and rate of braking force application at FFC and remains a key part of technique development during the bowling action. Therefore, higher release speeds may be related to an abrupt deceleration initiated via the front leg. This is potentially reliant upon lower body strength to attenuate and generate large forces.

Previously Callaghan et al. (2018) failed to demonstrate any effect of a periodised eight-week strength training program to change the GRF profile of fast-bowlers and influence ball speed. However, the current investigation found lower-body maximal strength—as assessed via absolute IMTP—was moderately positively correlated with pelvis COM acceleration during the delivery stride phase. This may suggest that increased strength levels facilitate a more abrupt deceleration and help the transfer of linear momentum from the run-up to angular momentum about joint segments through the kinetic chain and into the ball.

The ability to generate faster run-up speeds may facilitate a greater magnitude of deceleration at FFC and thus, increasing run-up speeds may be considered the first step towards increasing ball speed. Supporting this, *large* and *moderate* associations with ball speed were found for 10-30 m split time and 30m sprint, respectively. These findings support previous research by Feros (2015) who related ball speed with 20 m sprint performance (r=-0.409) in 31 community-standard fast-bowlers. A greater ability to reach higher maximal running speeds may allow fast-bowlers to maintain relatively faster run-up speeds and still execute fast-bowling technique; further justifying the use of sprint training in fast-bowler preparation (Bartlett et al., 1996, Feros, 2015). Interestingly, the current study revealed no significant relationships between run-up speed (pelvis COM velocity at BFC) and any of the sprint testing measures (10m, 10-30m split or 30m time) suggesting sprint ability does not necessarily relate to run-up speed. This may be due to technique-related factors at the penultimate step before BFC or variations across bowling action types such as front on bowlers being more reliant on run-up speed while side on bowlers use transverse plane rotational torque to generate ball speed (Elliott and Foster, 1984, Ferdinands et al., 2010). Regardless, sprint performance remains a factor for resultant ball speed and is an important component of the physical profile of fast-bowlers. However, ongoing investigations into the transfer of sprint speed into run-up speed remains an important consideration for researchers, coaches and athletes.

Increased run-up speed must also be considered with potential negative side effects to accuracy from the speed-accuracy trade-off (Brees, 1989). Furthermore, emphasising an increased run-up speed may lead to increased demands being placed upon the strength and stability of the front leg during FFC with increased GRF. According to Portus et al. (2004), fast-bowlers who suffered from stress fracture injuries demonstrated non-significant trends towards faster rates of peak braking and vertical force development during FFC. Although, King et al. (2016) argued that higher ball speeds are not reliant on peak GRF, rather braking impulse during FFC, which may not necessitate an increased risk of injury. Nonetheless, any changes to technique in the pursuit of increased ball speeds may come with unexpected consequences that should be considered before a training program is commenced.

In order to generate the requisite forces to bowl fast, it has been hypothesised that fast-bowling necessitates a relatively high level of strength (Johnstone et al., 2014). However, previous studies have typically failed to report associations between ball speed and strength, often due to inexperienced participants or limited strength testing conducted. The results of the current study are one of the few examples of a significant *moderate* association between lower-body maximal strength (via IMPT) and ball speed. Pyne et al. (2006) also reported relationships between lower-body strength and ball speed in both senior and junior fast-bowlers. However, they used a single leg Smith machine squat jump to assess isoinertial strength, as many of the participants were inexperienced with heavy strength training and did not report the bivariate relationship between factors. Loram et al. (2005) (high-school fast-bowlers n=12) and Wormgoor et al. (2010) (premier league fast-bowlers n=28) did not report any associations between ball speed and lower-body strength in knee flexion or knee extension torque during isokinetic dynamometry testing. Finally, Feros et al. (2019) used 3RM Smith machine half squat (124.2 ± 35.8 kgs) and reported no relationship with ball speed; again citing a lack of training experience as a potential factor in this study. This investigation used multi-joint, isometric maximal strength testing in a cohort of high-level fast-bowlers who also have extensive strength training history, suggesting that lower-body maximal strength may be associated with ball speed in higher-level athletes. While this relationship is associative, there does exist an extensive theoretical basis for suggesting physical performance coaches should consider multi-joint, maximal lower-body strength development in the training of fast-bowlers (Suchomel et al., 2016).

There were several physical attributes that were not associated with ball speed, namely VJ height and bench pull 1RM strength. The absence of a relationship between ball speed and VJ is similar to that of previous research (Pyne et al., 2006) and while jump height is generally used as an assessment of lower-body power (Cronin and Hansen, 2005), the lack of specificity to the fast-bowling action may preclude such associations. Furthermore, upper-body strength tests involving forceful shoulder extension (Feros, 2015) and internal rotation torque (Wormgoor et al., 2010) have demonstrated positive relationships with ball speed. Such actions better correspond to the shoulder circumduction dynamics of movement of the bowling action than the bench pull test. Additionally, fast-bowlers who deliver the ball at higher speeds have greater upper-body lean muscle mass, larger arm girths and wider chests supporting the need for an athletic build (Pyne et al., 2006, Portus et al., 2000, Stuelcken et al., 2007). The current assessment of upper-body strength using a maximal bench pull test did not relate to ball speed, hence, it appears that the methodology for measuring upper-body strength in fast-bowlers should involve the assessment of shoulder extension and/or internal rotation strength. Future research considering the role of upper body strength in fast-bowling ball speed generation should apply the principle of dynamic correspondence when selecting tests (Suarez et al., 2019). The authors suggest exercises like the bench press, chin-up or dumbbell pull over may better target the key muscles and vectors of force production for fast-bowling than the test used in the current study.

Finally, despite these novel findings, certain limitations need recognition. In particular, these relate to the number of physical capacity measures tested, the moderate heterogeneity of the participants (not all were professional players) and the comprehensiveness of the kinetic, kinematic and temporal fast-bowling technique analysis. With respect to the technique analysis, no GRF data was collected for BFC and temporal landmarks may have been influenced by differences in technique. For instance, one participant used a forefoot striking FFC technique with no heel touch down making the definition of FFC based on the heel marker inconsistent from other participants. Future research should use the methods outlined by King et al. (2016) to address this issue. Future research should aim to remedy these areas for a more holistic interpretation of the fast-bowling action and underlying physiological and mechanical components of performance.

In conclusion, both technical and physical fitness components were related to ball speed with bowling action duration and 10 – 30 m sprint split time accounting for more than half of the variation found in ball speed. Furthermore, specific technique factors that facilitated increased generation and retention of linear momentum, large and abrupt application of GRF, reduced duration of key phases of the bowling action and higher pelvis deceleration at FFC led to superior ball speed. Furthermore, lower-body strength may play a role in influencing the kinetics of the FFC phase in the fast-bowling action. Finally, sprint speed and maximal lower-body strength may be important physical fitness qualities to be developed for fast-bowling.

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Table 1. Temporal and kinetic variables and their correlation with ball speed in fast-bowlers (n=20)

Bowling technique variables	Mean ± SD	Range	Pearson Correlation	95 % Confidence Intervals		Sig. (2-tailed)	Description
				Lower Bound	Upper Bound		
Delivery stride length (m)	1.54 ± 0.12	1.30 – 1.83	0.203	-0.263	0.592	0.392	Small
Delivery stride length (% of standing height)	80.6 ± 5.8	70.8 – 92.9	0.172	-0.293	0.571	0.469	Small
Delivery stride duration (s)	0.18 ± 0.03	0.13 – 0.24	-0.547*	-0.797	-0.138	0.012	Large
FFC-BR phase duration (s)	0.07 ± 0.01	0.06 – 0.10	-0.602*	-0.825	-0.217	0.005	Large
Bowling action duration (s)	0.26 ± 0.04	0.20 – 0.32	-0.639*	-0.843	-0.274	0.002	Large
Pelvis COM velocity at BFC ($m \cdot s^{-1}$)	5.48 ± 0.70	4.38 – 6.82	0.616*	-0.832	-0.238	0.004	Large
Pelvis COM velocity at FFC ($m \cdot s^{-1}$)	3.71 ± 0.57	2.25 – 4.59	0.221	-0.245	0.604	0.350	Small
Pelvis COM velocity at BR ($m \cdot s^{-1}$)	2.49 ± 0.40	1.48 – 3.09	0.160	-0.304	0.563	0.501	Small
Peak pelvis COM velocity (BFC – BR) ($m \cdot s^{-1}$)	6.27 ± 0.75	5.11 – 8.03	0.469*	0.033	0.755	0.037	Moderate
Pelvis COM acceleration (delivery stride phase) ($m \cdot s^{-2}$)	-10.18 ± 4.97	-20.30 – -2.10	-0.582*	-0.815	-0.188	0.007	Large
Pelvis COM acceleration (FFC-BR phase) ($m \cdot s^{-2}$)	-16.46 ± 6.58	-27.37 – -3.27	-0.262	-0.631	0.204	0.264	Small
Pelvis COM acceleration (Vel_{peak} – BR) ($m \cdot s^{-2}$)	-23.11 ± 5.51	-32.76 – -12.20	-0.379	-0.704	0.076	0.099	Moderate
BFC time (s)	0.17 ± 0.03	0.12 – 0.23	-0.608*	-0.828	-0.226	0.004	Large
Peak GRFv (N)	5028 ± 610	3957 – 6034	0.370	-0.087	0.698	0.108	Moderate
Peak GRFv, normalised (BW)	5.5 ± 0.7	4.3 – 6.6	0.382	-0.073	0.705	0.097	Moderate
Peak GRFv time (% of action)	67.4 ± 3.4	61.3 – 74.3	-0.461*	-0.750	-0.023	0.041	Moderate
Peak horizontal breaking force (N)	1913 ± 309	1572 – 2771	0.397	-0.055	0.714	0.083	Moderate
Peak horizontal breaking force time (% of action)	67.2 ± 3.2	61.2 – 73.6	-0.538*	-0.792	-0.125	0.014	Large

* Correlation is significant at the 0.05 level (2-tailed). COM = centre of mass, BFC = back foot contact, FFC = front foot contact, BR = ball release, Vel_{peak} = peak velocity, GRFv = vertical ground reaction force, BW = x bodyweight

Table 2. Kinematic variables and their correlation with ball speed in fast-bowlers (n=20)

Bowling technique variables	**Mean ± SD**	**Range**	**Pearson Correlation**	**95 % Confidence Intervals**		**Sig. (2-tailed)**	**Description**
				Lower Bound	**Upper Bound**		
Front knee flexion/extension angle FFC (°)	6.2 ± 9.5	-12.4 – 18.7	-0.282	-0.644	0.183	0.228	Small
Front knee flexion/extension angle BR (°)	13.6 ± 20.6	-17.4 – 52.4	-0.063	-0.492	0.390	0.793	Trivial
Front knee minimum angle FFC – BR (°)	25.7 ± 21.5	-11.5 – 68.6	-0.075	-0.501	0.380	0.752	Trivial
Lumbar flexion/extension FFC (°)	-7.1 ± 12.5	-37.7 – 15.8	-0.334	-0.677	0.127	0.150	Moderate
Lumbar flexion/extension BFC (°)	2.9 ± 13.1	-25.0 – 29.4	-0.386	-0.708	0.068	0.093	Moderate
Peak trunk lateral flexion FFC – BR (°)	32.5 ± 4.8	21.4 – 41.7	0.411	-0.039	0.722	0.072	Moderate
Pelvis orientation BFC (°)	62.8 ± 14.1	30.8 – 87.7	0.293	-0.172	0.651	0.209	Small
Trunk lateral flexion FFC (°)	18.9 ± 6.2	5.6 – 27.1	0.321	-0.142	0.0669	0.168	Moderate
Trunk lateral flexion BR (°)	26.3 ± 5.8	13.1 – 33.9	0.141	-0.322	0.549	0.554	Small
Trunk lateral flexion ROM (°)	7.5 ± 9.7	-9.5 – 28.0	-0.119	-0.590	0.267	0.617	Small
Hip-shoulder separation FFC (°)	19.4 ± 12.3	-2.2 – 45.7	-0.087	-0.510	0.370	0.716	Trivial
Shoulder rotation BFC (°)	43.5 ± 14.4	19.0 – 62.9	0.360	-0.098	0.692	0.119	Moderate
Shoulder counter-rotation BFC – FFC (°)	31.5 ± 9.1	10.9 – 45.2	0.242	-0.225	0.618	0.305	Small
Ball release height (m)	1.97 ± 0.11	1.71 – 2.16	-0.222	-0.605	0.245	0.346	Small

* Correlation is significant at the 0.05 level (2-tailed). BFC = back foot contact, FFC = front foot contact, BR = ball release

Table 3. Physical fitness variables and their correlation with ball speed in fast-bowlers (n=20)

Physical capacity variables	Mean ± SD	Range	Pearson Correlation	95 % Confidence Intervals		Sig. (2-tailed)	Description
				Lower Bound	Upper Bound		
10 m sprint time (s)	1.84 ± 0.07	1.72 – 1.98	-0.373	-0.700	0.083	0.105	Moderate
30 m sprint time (s)	4.32 ± 0.18	3.91 – 4.66	-0.482*	-0.762	-0.050	0.031	Moderate
10 - 30 m sprint split time (s)	2.47 ± 0.12	2.19 – 2.69	-0.554*	-0.800	-0.148	0.011	Large
Vertical jump height (m)	0.59 ± 0.08	0.49 – 0.84	0.403	-0.048	0.718	0.078	Moderate
IMTP (N)	3379 ± 502	2539 – 4268	0.471*	0.036	0.756	0.036	Moderate
IMTP, normalised (BW)	4.03 ± 0.34	3.12 – 4.81	0.426	0.024	0.751	0.061	Moderate
Bench pull 1RM (kg)	82.1 ± 9.5	65.0 – 97.5	0.020	-0.426	0.458	0.934	Trivial
2 km-TT (s)	460 ± 47	402 – 614	0.130	-0.332	0.541	0.585	Small

* Correlation is significant at the 0.05 level (2-tailed). Note: IMTP = isometric mid-thigh pull, 1RM = one repetition maximum, TT = time trial, BW = x bodyweight

Table 4. Stepwise linear regression for ball speed in cricket fast-bowlers

Variable	**R^2**	**R^2 adjusted**	**p-value**
Bowling action duration	0.401	0.367	0.003
10 – 30 m sprint split time	0.543	0.490	0.001

Figure 1. Marker placement for 3D motion analysis of fast-bowlers

[redacted]